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The Three-Dimensional Structure of Our Galaxy

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Abstract. This presentation has the following goals: (i) to explain, within a historical context, some of the difficulties in disentangling our Galaxy's three-dimensional structure; (ii) to summarise in broad terms what we presently know of this structure, concentrating on those features inferred from accurate distance measurements; (iii) to illustrate selected aspects in a visually stimulating manner; and (iv) to give a foretaste of the exciting results that lie ahead with future space astrometric experiments.

1. Historical Introduction

We have, of course, come a long way since mankind first began to reflect on the nature of the stars. Plato's contemporaries observed that the heavens rotated night after night with constant speed. Myriads of fixed stars shared this rotation, preserving their relative positions without change. Moving amongst them in a puzzling way were the seven wanderers: the Sun, the Moon, Mercury and the other planets.

In the early 1600s, Galileo turned his telescope to the Milky Way, and discovered that it could be resolved into innumerable faint stars. By the mid-eighteenth century Thomas Wright had described our Galaxy as a disk of stars in which the Sun is immersed, and Immanuel Kant postulated the existence of other 'island universes' distributed throughout space at enormous distances. William Herschel used star counts in different sky regions to deduce the relative dimensions of our Galaxy, based on the crucial but incorrect assumption that all stars had the same absolute brightness.

A little more than a hundred years ago, Kapteyn was able to use the medium of astronomical photography to initiate a new, quantitative discussion of our Galaxy's structure. Massive observational programmes, such as the great Durchmusterungen and the Carte du Ciel, were set up. The size of our Galaxy, and the distance scale within it, became issues of great debate. Interpretation was complicated by problems of interstellar extinction, and the different luminosity classes and kinematic populations.

We now know that billions of stars, as well as planets, interstellar gas and dust, radiation, and invisible material, are gravitationally bound to form our Galaxy – a magnificent disk spiral system, supported by rotation. Our Solar System lies far out in one of the spiral arms, 30 000 light-years from the centre. Great debates continue, with the nature of dark matter, and the details of galaxy formation, star formation, and spiral structure, amongst them.

Our current picture is that the Universe originated from a hot, dense, and smooth state, the Big Bang. Structure originated from fluctuations in energy density during an early inflationary period, growing by gravitational amplification as the Universe expanded. Cooling and condensation of gas in the cores of heavy halos, produced by hierarchical clustering of dark matter, somehow finally resulted in the dramatic diversity of galaxy types that we see today.

Remarkably, the origin, past evolution, present-day structure, and long-term future of our Galaxy can be examined by direct observation (such results are also of value as a template for cosmological studies on much larger spatial scales). Low-mass stars, below about $1M_\odot$, live for longer than the present age of the Universe, and therefore preserve a chemical record of the elements and conditions from which they formed. Similarly, stellar motions reflect the large-scale components and kinematics of our Galaxy, trace out the otherwise unobservable distribution of dark matter, and contain a memory of events such as the epoch and rate at which our Galaxy has grown by devouring its smaller companions. Unravelling these clues requires distances to the stars, and the measurement of distance recurs throughout historical and current efforts to disentangle and interpret astronomical observations. Observational progress is still immensely constrained by the limited stellar samples at our disposal, by the range of populations for which good quality data are available, and by the precision with which distances and therefore the details of the stellar populations are known.

Observers, and even the most powerful ground and space telescopes, see celestial objects projected in two dimensions. Geometric distances can only be derived from the tiny oscillation in a star's apparent position arising from the Earth's motion around the Sun – the combination of this motion, and the motion of stars through space, then leads to a continuous evolution in a star's position. For two or more stars in the same field, their parallactic motions are in phase, and their relative angular separations yield only their relative distances, independently of how the stars are moving. However, superposing two widely separated fields on the sky allows absolute parallaxes and hence absolute distances to be measured. High accuracy, long-term monitoring of two-dimensional star positions therefore provides the pieces of a celestial jigsaw encapsulating a six-dimensional stereoscopic map of the stars and their motions through space.

What follows, directly from the observations or indirectly from modelling or theory, are absolute physical stellar characteristics, such as luminosities, radii, masses, and ages. Our goals are then to use these quantities to determine their physical composition and structure, to disentangle their motions and, eventually, to explain how our Galaxy formed, and how it will evolve in the future. We can then use these data to try to answer the questions posed so succinctly by Jan Oort: What is the distribution of matter? Why is it what it is?

Let me briefly place our present understanding of three-dimensional measurements in a broader historical context. 300–400 years ago, three main themes motivated the improvement of angular measurements: navigational problems associated with the determination of longitude on the Earth's surface, the comprehension and acceptance of Newtonianism, and understanding the Earth's motion through space. Even before 1600, there was general agreement that the crucial evidence needed to detect the Earth's motion was the measurement of trigonometric parallax. But for about 250 years, ambitious attempts to measure the first stellar distances were unsuccessful. In 1718 Edmund Halley, who had been comparing contemporary observations with those that the Greek Hipparchus and others had made, announced that three stars, Aldebaran, Sirius and Arcturus, were displaced from their expected positions by large fractions of a degree. Halley deduced that these stars had their own distinct velocity across the line of sight, or proper motion: stars were moving through space.

By 1725, angular measurements had improved to a few arcsec, making it possible for James Bradley to detect stellar aberration, as a by-product of his unsuccessful attempts to measure the distance to the bright star γ Draconis. This was an unexpected result – small positional displacements were detected, and correctly attributed to the vectorial addition of the velocity of light to that of the Earth's motion around the Sun. His observations supplied the first direct proof that the Earth was moving through space, and thus provided an unexpected confirmation both of Copernican theory, and Roemer's discovery of the finite velocity of light 50 years earlier. It also confirmed Newton's insight into the incomprehensible immensity of stellar distances, and showed that the measurement of parallax would pose a technical challenge of extraordinary delicacy.

During the eighteenth century the motions of many more stars were announced, and in 1783 William Herschel found that he could partly explain these effects by assuming that the Sun itself was moving through space. The early 1830s saw the formulation of criteria for estimating proximity, based on brightness and high proper motion, and eventually, the determination of the first parallaxes. Confirmation that stars lay at very great but nevertheless finite distances represented a turning point in the understanding of the Universe. John Herschel greeted the first distance measurements with the comment that *'the sounding line in the Universe of stars had at last touched bottom'*.

Measuring stellar distances remains exceedingly difficult, even within our Solar neighbourhood. William Herschel attempted to convey the unimaginable interstellar distance scales as follows: *'To drop a pea at the end of every mile of a voyage on a limitless ocean to the nearest fixed star, would require a fleet of 10 000 ships, each of 600 tons burthen.'*

One hundred and fifty years after the first stellar parallaxes were measured, and after a long period of painstaking ground-based efforts to map the Solar neighbourhood, space observations, beyond the effects of the Earth's atmosphere, are carrying this quantitative exploration forward. From a dense network of angular measurements, Hipparcos has provided tens of thousands of accurate distances and motions, with angular accuracies of around 1 milliarcsec. This is just the latest step in continuing efforts to measure distances across the enormous gulfs of space and time but, as we shall see, it places many old problems on a somewhat more secure observational footing.

2. The Main Components of our Galaxy

So let us look at some details of our Galaxy's structure as we understand them today. Various lines of argument show that on its largest scales, our Galaxy comprises two main structural elements, both roughly axially symmetric: a flattened disk, and a spheroidal component. On a clear dark night the projection of our own disk is perceived as a band of light across the sky, albeit heavily obscured by dust. The spheroidal component is generally pictured as comprising various sub-components, ranging from the nucleus of order 3 pc in size, through the bulge of order 3 kpc, out to the halo extending to 30 kpc or more. The relative importance of the disk and spheroidal components accounts for much of the observed variety in galaxy morphologies. Each contains quite different and characteristic stellar populations, and they have different compositions, kinematic and dynamic properties, evolutionary histories, and spatial sub-structures.

The halo consists of some billion old metal-poor stars, about 140 globular clusters, and a small number of satellite dwarf galaxies. Unless our present understanding of gravitation is incorrect, the flat rotation curves of gas in the outer parts of spiral galaxies imply that the entire systems are embedded in massive quasi-spherical outer halos of dark material. It appears to account for about 95% of the mass of the Galaxy and, for compatibility with standard nucleosynthesis, is believed to be non-baryonic. Otherwise it is of unknown composition and poorly known spatial distribution, and its mysterious character is one of the fundamental unanswered questions of our day.

From the southern hemisphere, the stellar bulge is partly visible to the naked eye in the direction of Sagittarius. The bulge is inferred to be triaxial, and appears to contain a bar-like structure. At its centre lies a black hole of about 3 million Solar masses. But studies are greatly hampered by its immense distance, by extreme reddening, and by the presence of the central parts of the disk and the halo, and it is unclear whether the bulge is a remnant of a disk instability, a successor or a precursor to the stellar halo, or a merger remnant.

2.1. The Disk: Large-Scale Structure

The most conspicuous component of the Milky Way is, however, the flat disk, representing most of the stars seen by eye and in photographs. Here our knowledge is somewhat more certain, especially in the local Solar neighbourhood. About 200 pc thick, the disk contains some hundred billion stars orbiting the Galactic centre, extending to radial distances of about 30 kpc. This disk is thought to have been formed by the rapid collapse of a rotating, galaxy-sized gas cloud, about 8–12 billion years ago. Star formation has been reasonably continuous since then, and as a result the disk contains stars with a range of metallicities, ages and kinematics.

The entire system is in a state of rapid differential rotation, with our Solar System completing a Galactic orbit every 240 million years. The prominent spiral arms are the primary locations of star formation, funneling mass from the gaseous component to the stars, and propagating such that the overall Galaxy appearance probably remains much the same for many rotation periods. Radio and mm observations of interstellar gas have delineated this spiral structure, and have mapped a significant warping of the Galactic disk outside the Solar orbit. While about half of all spiral galaxies display such warps, there is no detailed explanation of this common phenomenon. Hipparcos has provided hints of the spatial and kinematic distribution of the local Orion arm, but with accurate distances out to only a few hundred parsec, we are far from having a detailed map. Our fuzzy perception of local spiral structure based on photometric distances should be replaced by a much sharper view once distance accuracies at tens of microarcsec become available.

The Sun and the nearby stars move with respect to our 'local standard of rest', which itself moves around the centre of the Galaxy with a velocity of about 220 km s^{-1}, one revolution every 240 million years. The mean-free time between collisions for the Sun in the Solar neighbourhood is of order 10^{13} years, very much longer than the present age of the Galaxy, so stars here behave as a collisionless gas. In the Solar neighbourhood, space velocities with respect to the local standard of rest tend to increase with time, due to accumulated perturbations from other stars, giant molecular clouds, and spiral arms. Free from kinematic biases, which in the past have plagued studies of local stellar kinematics, Hipparcos has revealed that the local stellar velocity distribution is highly structured and complex, with both the stellar warp outside the Solar circle, and the bar in the inner Galaxy, having left their imprints (Dehnen & Binney 1998).

There are a number of curious aspects of our Sun's space motion within the disk, which have been pointed out by Gonzalez (1999). First, its velocity, 13.4 ± 0.4 km s^{-1}, is unusually small. Second, it lies at a vertical height of only 10–12 pc from the Galaxy mid-plane (Reed 1997), even though it must have oscillated up and down across the disk many times throughout its history. And as deduced from the Cepheid proper motions, our Sun lies very close (to within 100 pc) to the Galaxy's co-rotation resonance, where the rotation velocities of the disk and of the spiral pattern coincide (Mishurov & Zenina 1999). These properties suggest that our Sun may have a privileged Galactic orbit, possibly with interesting habitability and anthropic implications (Gonzalez 1999).

What is called the thin disk accounts for about 90% of the visible light in the Milky Way, but only about 5% by mass. Since the 1980s we have come to recognise a faint, thick disk of old stars (Gilmore & Reid 1983). Although the thick disk includes some of the oldest stars in the Galaxy, their provenance is uncertain: some may have formed *in situ*, some may have been scattered from the thin disk, while the majority may have originated from a galaxy which merged with our own around 9 billion years ago, leading to an abrupt increase in velocity dispersion. This is seen once the Hipparcos motions are combined with precise age estimates from isochrone modelling (Quillen & Garnett 2001). The possible diversity of histories of the thin and thick disks, and their complex distribution of chemical abundances and kinematics, is presently very difficult to disentangle.

2.2. The Disk: Small-Scale Structure

In practice, little is known about the stellar disk beyond 1–2 kpc from the Sun. This is due to significant interstellar extinction towards the central regions, and by our inability to determine accurate distances and space motions for objects so far away. Much more is known about the local small-scale structure, including star forming regions, open clusters, expanding associations, and stellar streams.

Open clusters contain a few tens to a few thousand stars, born in the same molecular cloud and gravitationally bound. They are tracers of the young and intermediate-age disk components of the Galaxy, with ages ranging from a few million to a few hundred million years. Members are coeval, have the same chemical composition as the parent cloud, share the same bulk space motion to within the internal velocity dispersion of the cluster (a few tenths of a km s^{-1}), with members distributed across the whole mass spectrum, from brown dwarfs to A, B or O stars, depending on age.

In the case of the Hyades, at about 46 pc, the cluster's proximity, high proper motion, and high space velocity with respect to its own local standard of rest, allow members to be identified with relative ease. Members form a coherent structure in velocity space, inheriting their bulk motion from the parent molecular cloud. Various methods can be used to identify these groups using their measured positions and velocities. The development of these coeval systems, both dynamically and with respect to temperature and luminosity, provide ideal laboratories for testing models of stellar evolution. They 'evaporate' and eventually disintegrate over tens or hundreds of millions of years due to mass loss by stellar evolution, due to gravitational encounters between stars in the cluster, and due to tidal forces between the cluster and the Galactic disk or giant molecular clouds.

The Hertzsprung-Russell Diagram for the Hyades is now beautifully delineated on the basis of the accurate individual trigonometric parallaxes, which resolve the depth of the cluster along the line of sight (Perryman et al. 1998). Characteristics such as the helium abundance and cluster age can be inferred. Combining trigonometric distances with the proper motions, the HR diagram can be further tightened, with interesting consequences for the understanding of stellar evolution (Dravins et al. 1999; de Bruijne et al. 2001).

More than a thousand open clusters are known, but only half have reasonable distance estimates, with most closer than 2 kpc. At about 110 pc, even the Pleiades is too far away for individual distances to be measured with any degree of significance, but classifying stars according to bound members and evaporating objects starts to become possible.

O and B stars are not randomly distributed among the Galactic stellar populations, but generally as unbound associations of young stars. Members can again be detected kinematically because of their small internal velocity dispersion, although nearby associations have a large angular extent on the sky, which has traditionally limited membership determination to bright stars and early spectral types. Recent studies have led to significantly improved membership determination, including extension to later spectral types, and improved mean distances out to 600–700 pc (de Zeeuw et al. 1999). Studying the formation, structure, and evolution of these young stellar groups and star-forming regions is important since as much as 90% of the stars in the Galaxy may have formed in OB associations. Like bound clusters, these slowly dissolve into the field population as a result of Galactic tidal forces.

Dense young clusters are also the birthplace of high-velocity 'runaway' stars. These may originate either via dynamical encounters, or in the unbinding of a binary after a supernova explosion of one component. The runaway stars AE Aur and μ Col, at distances of about 500 pc, are now some 100° apart on the sky, receding at about 100 km s^{-1}. Careful extrapolation backward in time provides strong evidence for a common origin. They were probably ejected in a dynamic encounter with the massive binary ι Orionis, in the heart of the Orion OB1 association, 2.2 million years ago (Hoogerwerf et al. 2001). Nearly 200 runaway stars are known, often at very significant distances from young stellar groups, but current measurement accuracies do not generally make it possible to retrace their orbits meaningfully and understand their origins.

2.3. The Stellar Halo

The baryon halo (including blue horizontal branch stars, RR Lyrae variables, metal-weak red giants, and globular clusters) rotates very slowly compared to the disk – some have suggested that it may even be counter-rotating – and extends outwards to a radius of perhaps 100 kpc or more. Although comprising only some 2% of the light, and an even smaller fraction of the total mass, the stellar halo plays a key role in unravelling the sequence of events involved in galaxy formation.

Within the halo, globular clusters are dense swarms of about 100 000 stars, and are possibly relics of intergalactic ingredients added to the Milky Way after its creation. Far older than any fossil on Earth, older than any other structures in our Galaxy, some are so old that they have challenged age estimates of the Universe itself. Ages of the oldest, metal-poor globular clusters, in the inner and outer halo, the Large Magellanic Cloud, and the nearby Fornax and Sagittarius dwarfs show a remarkable uniformity. To within about 1 Gyr the onset of globular cluster formation appears to have been well synchronised over a radius of more than 100 kpc.

Globular clusters are too far away for distances to be measured trigonometrically today. Instead, distances and hence luminosities of nearby field sub-dwarfs are used to estimate the distances of globular clusters through main-sequence fitting. For this, one needs a template main-sequence, from nearby metal-poor sub-dwarfs, of which Hipparcos has provided distances to about 100. Nevertheless, numerous complications make the chain of deduction from sub-dwarf distances to globular cluster ages far from straightforward (Reid 1999).

3. Nearby Stars

Our understanding of nearby stars has focussed on the 'Catalogue of Nearby Stars' maintained by Heidelberg astronomers since Wilhelm Gliese established his first such catalogue census there in 1957. Extending out to a distance of 25 pc, and cataloging some 2000 stars, the original compilations had to draw on painstaking ground-based parallax determinations extending over about one century, assembled from observations at many different observatories, and supplemented by spectroscopic or photometric distance estimates. The goal in such a census is to identify, from the two-dimensional projection of the hundreds of millions of stars on the celestial sphere, that small subset lying within 25 pc. While this corresponds to a vast region of space extending out to nearly 10^{15} km, it is minute on astronomical scales, extending to less than 0.3% of the distance to the Galactic centre, and including barely 10^{-8} of its total stellar content.

Seeing nearby space with enhanced stereoscopic vision we can simply pick out our nearest neighbours (Jahreiß & Wielen 1997). Around 200 'new' nearby stars within 25 pc have become apparent, the nearest of these, HIP 103039, lying at a distance of only 5.5 pc. Several hundred stars previously suspected of being on our doorstep are now known to lie much further away. There are fewer main sequence stars, and a reduction in the number of giants within 20 pc by almost a factor of two. One white dwarf is expelled from the 5 pc sphere, and 37 previously unknown binary companions have entered the 25 pc census. The local stellar mass density has 'decreased' to a value of about 0.039 $M_\odot$ pc^{-3}.

4. Distance Scale

Cepheid variables play a crucial role as distance indicators. They are of high intrinsic luminosity, hence observable out to very large distances, but relatively rare, with few within reach of accurate trigonometric distance determinations. A plot of velocity in Galactic longitude versus Galactic longitude for the 220 Hipparcos Cepheids shows a pronounced sinusoidal structure beautifully illustrating Galactic rotation (Feast & Whitelock 1997), with fainter and redder objects being more distant along the lines of sight through the Galaxy disk.

We can see how the same Cepheids participate in the overall rotation of our Galaxy by using distances from the period-luminosity-colour relation, velocities with respect to our own local standard of rest, and then extrapolating their instantaneous space velocities to circular motion over a period of, say, 100 million years. Effectively derived from this fairly complex pattern, the Oort parameters describing Galactic rotation imply a Galactic centre distance of about 8.5 kpc, with an uncertainty of about 5% (Feast & Whitelock 1997). Transforming the measured velocities to a Galactic centre origin, a much more structured extrapolated motion is then evident, with the phenomenon of differential Galactic rotation clearly seen.

Well-behaved though these results appear, extending the trigonometric distance scale beyond our Galaxy, with any degree of precision, currently presents many puzzles. An early Hipparcos Cepheid-based distance for the Large Magellanic Cloud, of about 55 kpc, represented an upward revision of the extragalactic distance scale by nearly 10% (Feast & Catchpole 1997). Others have since used different Hipparcos tracers, for example, the RR Lyrae, Mirae, and red clump giants; and compared them with independent methods such as the SN 1987A ring and geometrically-derived orbital parallaxes (Walker 1998). No clear consensus has yet emerged, and an improved understanding of the physics of these various objects is certainly called for. At this distance the parallax is about 20 μarcsec, so that the Large Magellanic Cloud will not escape the direct embrace of SIM and GAIA in the future.

5. Distribution of Matter

All stars in the Galaxy move under the gravitational attraction of all other matter, and their motion therefore probes the gravitational signature of material irrespective of its physical manifestation. Visible stars and gas appear to make up only a small part of the total mass of galaxies, with most of it thought to be in some kind of dark form. The primary evidence is that disk galaxies rotate much faster in their outer parts than any reasonable model for the distribution of luminous matter allows. Our Galaxy's dark halo component may extend to at least 50 kpc, as traced by the Magellanic Clouds, and possibly to beyond Leo I at more than 200 kpc.

Locally, the distribution of mass is characterized by the mass per unit volume and, reflecting its scale height, its total surface density in a column perpendicular to the Galactic plane. These quantities are important for understanding chemical evolution, star formation, disk stability, and dark matter properties. Dynamical determination of the density of matter in the Solar neighbourhood, the 'K–z problem', aims to characterise the force law perpendicular to the Galactic plane. For a stellar population in equilibrium, its density and velocity distribution are connected via the gravitational potential, from which the dynamical density can be derived. Early investigations date back to the ideas of Kapteyn (1922), while Oort (1932) produced the first tentative determinations.

Hipparcos results have clarified the problem somewhat, based on a sample of 3000 A and F stars extending out to 125 pc, and including A stars such as Sirius, β Arietis and Castor (Crézé et al. 1998; Bienaymé 1999; Holmberg & Flynn 2000). These stars are sufficiently luminous that they can be mapped at relatively large distances, whilst sufficiently numerous that they are well represented in the Solar neighbourhood. The sample provides a volume-limited and absolute magnitude-limited homogeneous tracer of stellar density and velocity distributions in the Solar neighbourhood, although these young stars may not be in gravitational equilibrium with the larger-scale Galactic potential. For a star making only a small excursion from the Galactic mid-plane, and moving with simple harmonic motion, the time taken to execute one oscillation is about 60 million years. The distance travelled from the mid-plane, for an initial velocity of 10 km s^{-1}, is about 100 pc. Detailed analyses indicate that the local dynamical density of matter near the Galactic mid-plane, the Oort limit, is around 0.1 $M_\odot$ pc^{-3}. The vertical motion of the nearby A and F stars is controlled by a projected mass density of about 80 g m^{-2}, equivalent to the thickness of normal writing paper.

Comparison with the sum of all observed local matter confirms that the bulk of the Galactic dark matter is distributed in the form of the halo, and not in the form of the disk. Uncertainties remain due to difficulties in detecting low-luminosity stars even very near the Sun, from the uncertain binary fraction among low mass stars, and from uncertainties in the stellar mass–luminosity relation. To summarise: the distribution of both visible and dark matter are still known with only modest accuracy, even in the Solar neighbourhood. Significant improvement requires accurate distances and velocities for a large sample of tracer stars to faint magnitudes, and to much larger distances.

6. Formation of the Galaxy

The Galactic disk is thought to have been formed by the rapid collapse of a rotating, galaxy-sized gas cloud, billions of years ago. The formation of the halo seems to be happening more slowly, and in a more piecemeal fashion.

Forty years ago, the high-velocity star Groombridge 1830 was discovered to belong to a moving group now passing through the Galactic disk (Eggen & Sandage 1959). At a distance of only 10 pc, this is the third highest proper motion star, moving with a space velocity of 300 km s^{-1}. At these high velocities, stars can travel many kpc from the Galactic plane before their motion is reversed by the overall gravitational field. All stars in the halo must pass through the disk periodically. Being in orbit around a disk star, we can observe halo visitors such as Groombridge 1830 during their rare visits to the Solar neighbourhood. In contrast, astronomers in orbit around a halo star would presumably get a magnificent view of the disk, but could only observe disk stars closely during their own rare passage through the Galactic disk.

Observations of objects like Groombridge 1830 were used to argue that the halo was created during the rapid collapse ($\sim 10^8$ yr) of a relatively uniform isolated protogalactic cloud shortly after it decoupled from the universal expansion (Eggen et al. 1962). During the last two decades, more kinematic and abundance evidence has become available, and stellar archaeologists are guided more by models which argue that the halo has been built up over billions of years from infalling debris (Searle & Zinn 1978). Evidence includes coherent moving groups in the halo, such as that found towards the North Galactic Pole (Majewski et al. 1994), and the elongated stellar stream of the Sagittarius dwarf spheroidal, which is moving through the plane on the far side of the Galaxy and is presently being disrupted by the Galactic tidal field (Ibata et al. 1994).

Part of the evidence for this comes from satellite galaxies encircling our own, and apparently confined to two great streams across the sky. The Magellanic Clouds and the associated Magellanic Stream, as well as Ursa Minor, Draco, and Carina, may be the debris from a former, greater Magellanic Galaxy, which is expected to merge with our own in the distant future due to dynamical friction of the extended halo, somewhat analogous to the existence of comet and meteor streams in a single orbit around the Sun. The Fornax-Leo-Sculptor stream, along with some of the young halo globular clusters, may also be related through a common Galactic accretion event (Lynden-Bell 1982; Majewski 1994; Lynden-Bell & Lynden-Bell 1995).

In our present picture of how the Galaxy materialised out of the hot, dense, early Universe, the outer parts of galaxies are thought to be accreting low-mass objects ($10^7 - 10^8\,M_\odot$) even at the present time. Since the orbital time scales of stars in the outer parts of the Galaxy are several billion years, it is here in the baryon halo that we would expect to find fossil evidence of the surviving remnants of accretion, and hence the most compelling evidence to distinguish among competing scenarios for our Galaxy's formation.

Rather direct evidence for such a merging event has recently become available. From the proper motions of 275 metal-poor stars within 2.5 kpc of the Sun, distributed all over the sky with no obvious spatial or velocity structure, Helmi et al. (1999) identified 13 metal-poor stars strongly clumped in angular momentum space (see also Chiba & Beers 2000). Their velocities, of around 300 km s^{-1}, are similar, since they all have roughly the same kinetic energies, and roughly the same potential energy, all being in the Solar neighbourhood. These 13 stars are identified with a single coherent structure, which was captured during or soon after our Galaxy's formation. The satellite had a mass of about $4 \times 10^8\,M_\odot$, and was in a highly inclined orbit, with a maximum distance of only 16 kpc, and a pericentric distance of 7 kpc. As it orbited the Galactic centre, it left a trail of debris over a period of 3 billion years. About 10% of the metal-poor stars in the halo appear to come from this single collision. This type of complex phase-space structure should be revealed in detail by the next generation of astrometric space missions.

7. Miscellaneous

I include some examples of other topics for which three-dimensional imaging of our Solar neighbourhood has provided interesting results.

7.1. The Age of the Universe

A minimum age of the Universe, useful for constraining cosmological models, can be estimated by determining the age of the oldest objects in our Galaxy. Currently the best age estimates for the oldest stars is based on the absolute magnitude of the main-sequence turn-off in globular clusters, again requiring that the distance to the globular cluster be known (Chaboyer 1999). Results yield ages of the oldest clusters of around 11.5 ± 1.3 Gyr.

Independent ages of old objects can be obtained from nucleochronology, and from white dwarf cooling sequences (Winget et al. 1987; Richer et al. 1997; Richer et al. 1998), the latter method again needing precise distances. Higher accuracy in the future will provide accurate age estimates of the Galactic disk from stellar evolution modelling, and independently via white dwarf cooling curves, and their comparison should yield valuable constraints on any secular evolution of the gravitational constant, G (e.g. García-Berro et al. 1995).

7.2. General Relativity

The measurement of accurate distances and space motions is intimately tied up with the underlying fabric of space-time, and classical tests of light bending make use of the Solar eclipse configuration, in which star light is deflected by the gravitational field of our Sun. Hipparcos yielded a value of the light-bending term, γ, accurate to about 1 part in 10^3 (Froeschlé et al. 1997). To visualise the geometrical effect, first note that the presence of a gravitating mass deflects a stellar image radially outwards at any given instant. At a subsequent instant, when the mass has moved, displacements are again radially outwards – these radial displacements map into an intriguing time-dependent apparent motion as the gravitating mass moves. Similar stellar shifts would accompany the motion of halo black holes in the Solar neighbourhood, if dark matter exists in the form of primordial black holes formed before nucleosynthesis began.

7.3. Extra-Solar Planets

The idea that planets, and possibly intelligent life, exist beyond our Solar System, has stimulated scientific and popular imagination for centuries. Five years ago, the first extra-Solar planetary systems were discovered through the radial velocity variations of their photocentres. Any stellar companion – whether itself stellar, sub-stellar or planetary – will produce a periodic photocentric wobble in the system's linear barycentric motion through space. Superimposed on the star's linear proper motion, and parallactic ellipse, are additional perturbations due to any accompanying planets. Planet detections in their tens of thousands will be made by the next generation of global microarcsec astrometric satellites, yielding mass estimates independent of orbital inclination. Statistical access to planetary systems on this scale will advance our knowledge of planet formation, and should provide much insight into the formation of our own Solar System.

7.4. Close Passages and Oort Cloud

For stars passing near to the Sun, close passages through the Oort Cloud can deflect large numbers of comets into the inner Solar System, initiating Earth-crossing cometary showers and possible Earth impacts. Although the distribution of long-period cometary aphelia is largely isotropic, some non-random clusters of orbits do exist, and it has been suggested that groupings of long-period comet orbits record the tracks of recent stellar passages. Dynamical models suggesting typical decay times of around 2–3 Myr. These studies can probe the link between comet showers and past impact events and mass extinctions on Earth. Gliese 710 is the most significant known perturber in the future (García-Sánchez et al. 1999). Now at 19 pc from the Sun and moving directly at us at 14 km s^{-1}, it will pass through the Oort Cloud, at about 50 000 astronomical units from the Sun, in about 1 Myr. Algol, now receding from us, was our closest visitor in the recent past, coasting by at a distance of 2.5 pc about 7 Myr ago. Other past or future close passages will presumably be revealed once our knowledge of the kinematics of the local stellar population is more complete.

8. The Future

Notwithstanding the huge effort that has been required to improve the stereoscopic mapping of our Solar neighbourhood, I suspect that future generations will look back at the start of the 21st century, and still consider our present knowledge of stellar distances to be remarkably limited. New measurements are now planned that will go very much further.

As we proceed to probe this fractal phase-space jigsaw of stellar motions a host of higher-order phenomena will be uncovered. At the microarcsec level, direct distance measurements will be possible right across our Galaxy and out to the Large Magellanic Cloud. In the process, dynamical consequences of dark matter will become more recognisable, and we will encounter new effects such as perspective acceleration and secular parallax evolution, additional metric terms, planetary perturbations, and astrometric micro-lensing. At this level, even the Sun's absolute acceleration with respect to the Galactic centre, of 2 Å s^{-2}, will have an observable effect on the apparent positions of distant quasars. Further in the future, effects of interstellar scintillation, ripples in space-time due to gravitational waves, and geometric measurements at redshifts of order unity, will enter at the nanoarcsec level.

The bulk of this seething motion is largely below our current observational capabilities, but it is there, waiting to be investigated. Later this decade the US space experiments FAME and SIM, and hopefully the European mission GAIA, will carry these distance measurements forward. GAIA, for example, would not only provide distances to 10% for 15 mag stars at the distance of the Galactic centre, but will measure all stars in regions with up to about 3 million stars per square degree (i.e. everything down to 20 mag in Baade's Window), resulting in a catalogue of more than one billion objects complete to 20 mag, of which of order 100 million would have distance accuracies better than 5%.

Stereoscopic mapping at the microsecond level will certainly reveal many more important clues to our Galaxy's origin, structure, and future.

9. Illustrative Material

This lecture, in the Bridgewater Hall, Manchester, used a series of 2-d animations based on proper motions and derived parameters from the Hipparcos Catalogue, and a series of 3-d projections illustrating specific star fields and related distance-dependent effects. The latter employed a dual digital projection system, with orthogonally-polarised light beams and an 8m × 6m reflecting screen, with members of the audience equipped with appropriate polarised glasses.

Two-dimensional animations showed, for example, moving star fields over several thousand years, including Arcturus, the Hyades, Pleiades; reconstructed orbits of disk stars within the Galactic potential; motions of stars in a 20 pc cube centred on the Sun; simulations of the Galaxy's thin and thick disk populations; Cepheid motions with respect to the local standard of rest and the Galactic centre; space motions of local OB associations; runaway stars; the influence of planetary perturbations on a star's photocentric motion; and the effects of general relativistic light bending.

The stereoscopic projections included the moving fields of the Hyades and Pleiades, as well as 3-d images of the clusters Praesepe, Coma, IC 2602, IC 2391, and Alpha Persei; the paths of stars in the disk potential; A and F stars moving perpendicular to the Galactic plane under the influence of the disk potential; the motion of stars in the local Solar neighbourhood; nearby OB associations; and other specific fields including RR Lyrae, δ Cephei, β Doradus, X Sgr, β Arietis, Castor; sub-dwarfs HIP 78775 and HIP 74234/74235; white dwarfs 40 Eri B and V471 Tau; the space motions of Groombridge 1830 and the approaching star Gliese 710; the fields of the planetary systems 51 Peg, 70 Vir, 47 UMa and υ Andromedae; the constellations of Orion's Belt and Ursa Major; and the Hubble Deep Field in three dimensions based on spectroscopic redshifts.

Some example stereo images, using different viewing methods, can be found on the Hipparcos www site (`http://astro.estec.esa.nl/hipparcos`).

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