The participants at this conference can broadly be divided into three separate groups, working on the stellar halo, the gaseous halo, or the dark halo of our Galaxy. The organizers did an excellent job of bringing these groups together, and mixing the various topics throughout the sessions in such a way as to generate lively discussions. Together with the high-quality posters, this ensured there was much to learn for everyone. Summarizing all the material is a daunting task, but when Jeremy Mould pointed out what appeared to be a freshly-dug grave on Mount Stromlo the other day, and Phil (Tuco) Maloney reminded me of some memorable scenes in ‘The Good, the Bad, and the Ugly’ a few hours later, it was clear that there was no way out. I will discuss the luminous halo first, then review what we learned about the dark halo, touch briefly on the larger picture, and close with a look towards the future, with emphasis on the role of space astrometry missions.

1. Luminous Halo

The stellar halo of the Galaxy contains only a small fraction of its total luminous mass, but the kinematics and abundances of halo stars, globular clusters, and the dwarf satellites contain imprints of the formation of the entire Milky Way (e.g., Eggen, Lynden–Bell & Sandage 1962; Searle & Zinn 1978).

1.1. Field stars: abundances and ages

We have heard results from two long-term systematic programs on halo stars. The first is by Carney, Latham & Laird, and is based on 1450 kinematically selected stars for which radial velocities, proper motions, and abundance information have been collected, and orbits have been calculated. Beers, Norris and Ryan reported preliminary results based on a sample of 4660 objects from the HK Survey (Beers, Preston & Shectman 1992), for which radial velocities, broad-band colors and abundance indicators are available, but no proper motions (yet). These studies show that very few really metal–poor stars ([Fe/H] < −2.0) occur in the halo. Below [Fe/H] = −2.0 the numbers decrease by about a factor of 10 for every dex in [Fe/H]. Norris showed that despite much effort, and some false claims, there seems to be no evidence for stars significantly more metal poor than [Fe/H] = −4.0.

Measurements of detailed element ratios for [Fe/H] ≲ −3.0 reveal a significant range in C and N abundances at fixed [Fe/H], which may well reflect the localised shotnoise of individual enrichment events caused by early supernovae (e.g., Audouze & Silk 1995). This abundance variation is most evident in r-process elements, which suggests that it was put in place by Type II supernovae.
during the earliest epoch of star formation, before there was time for intermediate mass stars to return s-process elements to the interstellar medium. Laird showed that [O/Fe] measurements support this. This then suggests that the most metal-poor stars were indeed all formed in a short time interval (less than 1 Gyr), some 12–14 Gyr ago. However, Fujimoto argued that the observed abundance variations may also be caused by internal pollution during the evolution of very metal-poor stars.

Independent and more direct measurements of ages come from two sources. The HIPPARCOS parallaxes of nearby low-metallicity field halo stars allow them to be placed very accurately in the Hertzsprung–Russell diagram. Comparison with theoretical isochrones then results in ages between 11–13 Gyr (Reid 1997). The direct measurement of the Th/Eu ratio, which is a radioactive clock, gives similar ages (Cowan et al. 1997), albeit with a somewhat larger uncertainty.

1.2. Globular Clusters

Work continues on the ages and metallicities of globular clusters. Vandenberg described the latest improvements on the theoretical stellar models. Sarajedini reminded us that the [Fe/H]-scale has recently been recalibrated by Carretta & Gratton (1997). Fortunately, the correction relative to the earlier scale of Zinn & West (1984) is monotonic, but it is non-linear, and does affect not only the inferred ages of individual globular clusters, but also the commonly accepted properties of the ensemble of clusters. For example, the well-known bimodal [Fe/H] distribution of the disk and halo globular clusters may be much less pronounced than was generally assumed.

Piotto described results derived from systematic programs of ground-based and Hubble Space Telescope (HST) observations aimed at obtaining accurate and homogeneous color-magnitude diagrams that reach down deep enough to include the key regions that are used for age determinations. The main results are that (i) nearly all globular clusters show a remarkably small age-spread, of about 1 Gyr or less, (ii) the ages of the halo clusters do not correlate with [Fe/H], and (iii) there is a hint that the clusters at the largest galactocentric radii might be slightly younger. The globular cluster ages agree with those of the oldest and most metal-poor field halo stars, and with those of the oldest populations seen in the dwarf spheroidal companions. The debate on the precise value of the age of all these oldest populations continues (e.g., Mould 1998), but for the purpose of this summary, I will take it to lie in the range of 12–14 Gyr.

Assuming that the evolutionary tracks will continue to improve, there are two areas where progress can be made in the next few years. It became evident during the discussions that the various groups that are interpreting color-magnitude diagrams need to agree on a methodology, so that e.g., the same quantities are being measured. Secondly, the beautiful study of NGC 6397 by King et al. (1998) shows that HST proper motions based on WFPC2 images taken less than three years apart allow a clean separation of members and field halo stars, and provide a much improved color-magnitude diagram, extending significantly deeper than similar ground-based work (e.g., Cudworth 1997). This approach can easily be extended to other nearby clusters, in particular to Piotto’s large sample for which first-epoch exposures are already in the HST archive.
1.3. **Ghostly Streams**

Scenarios for galaxy formation suggest that the Galactic halo should contain substructure: extra-tidal material around globular clusters, tidally disrupted small satellites, and effects of the interaction of the Milky Way with the Large and Small Magellanic Clouds. Persistent hints for velocity clumping in high-\(|z|\) samples of field halo giants can be found in many papers over the past decade (e.g., Freeman 1987; Majewski, these proceedings). The discovery of the Sagittarius dwarf (Ibata et al. 1994), provided direct and dramatic evidence for a fairly massive dwarf galaxy that is in the process of tidal disruption in the Galactic halo. Mateo showed that the extension of Sgr can now be traced over 34 degrees and counting. Good kinematics and distances are needed to analyze this further. Grillmair et al. (1995) presented evidence for tidal streamers associated with globular clusters. Much work in this general area has been done by Majewski, who reviewed the evidence for retrograde/direct motion at high/low \(|z|\), and reported that the stars associated with the gaseous Magellanic Stream (§1.4) have now also been found.

The HIPPARCOS Catalog contains a few hundred local halo stars, and the accurate absolute proper motions combined with the available radial velocities allow analysis of their space motions. Chiba showed that while there are Galactic disk stars with \(-1.6 < \left[\text{Fe/H}\right] < -1.0\), there is no sign of the disk for \([\text{Fe/H}] < -1.6\), and little evidence for clumping in velocities (but see Helmi et al. 1999). The HIPPARCOS sample is small, and is somewhat of a mixed bag, so it is not easy to interpret the data. And, as Moody & Kalnajs illustrated in a poster contribution, one has to be very careful with extrapolating local halo measurements to larger distances.

The hints for substructure have triggered work to develop better detection methods. The Great Circle Method of Lynden–Bell & Lynden-Bell (1995), developed for spherical geometry, suggests that the satellite dwarf galaxies may not all be on independent orbits, but together occupy a small number of orbits, i.e., are parts of ‘ghostly streams’. Majewski showed that the orbits of the globular clusters display similar signatures. A natural next step is to apply this kind of analysis to individual stars with good distances and motions, such as the Carney, Latham & Laird (1996) sample.

Tidal stripping in a spherical potential is reasonably well understood, and was the main topic of the talk by Johnston. The spherical approximation applies at large galactocentric radii \(r\), and predicts a coherent structure in \(r\) and \(v\) space. Applications include the tidal tails of globular clusters and the Magellanic Stream. And as Zhao et al. showed in a poster contribution, if one knows which stars belong to the stream through independent means, the observed kinematics can be used to constrain the Galactic potential, but only if proper motions of sufficient accuracy are available.

The first results of a systematic observational program for finding substructure in the inner, flattened, halo, was presented by Harding et al., based on a strategy derived from N-body simulations of their ‘spaghetti’ model (which graced the announcement poster for this meeting). Helmi & White presented a powerful analytic formalism to analyze tidal disruption in a flattened potential. In this case a coherent structure remains in \(v\)–space, but not in configuration space. Picking out disrupted streams is therefore more difficult, but is possible
with good kinematic data which includes astrometry. The properties of the progenitor can then be inferred from the current measurements, and in this way one can hope to reconstruct the merging history of our own Galaxy.

There was much interest in the details of the encounter of the Large and Small Magellanic Clouds (LMC/SMC) with the Milky Way (MW). Weinberg showed preliminary results of a detailed analysis based on N-body simulations and normal mode calculations. He computed the effect of the LMC on the MW halo and disk, and finds that the LMC can induce the observed warp as well as lopsidedness in the Milky Way, provided the LMC is sufficiently massive. In turn, the MW tidal field puffs up the LMC. Weinberg finds a total mass of the LMC of about $2 \times 10^{10} M_\odot$, considerably larger than previous estimates, perhaps suggesting it has its own dark halo. Photometric evidence for a stellar halo around the LMC was presented by Olszewski. This is relevant for the interpretation of the observed microlensing events towards the LMC (§2.2).

Zhao described a scenario in which the Sgr dwarf was involved in an encounter with the LMC/SMC at a particular time in the past, which dropped it into a lower orbit. The a priori probability of this is modest, but it does tie together a number of apparently unrelated events, and provides a way for Sgr to survive long enough to be torn apart only in its current perigalacticon passage. It is intriguing that we may obtain an independent handle on these orbital issues by determination of the star formation history in the satellites. This may well have been punctuated by short bursts of star formation, coinciding with close encounters or merging. Clearly a full model is needed of the LMC/SMC/Sgr interaction with the MW, including both the stars and the gas (§1.4). The data to constrain this is quite detailed, and this nearest encounter may tell us much.

1.4. Gas: neutral and ionized

Many of the participants who work on properties of the gaseous Galactic halo attended the High Velocity Cloud (HVC) workshop at Mount Stromlo, just prior to this meeting. For a detailed summary, see Wakker, van Woerden & Gibson (1999). A number of key results were presented again during this Symposium, and I will mention these briefly.

For many years the distribution of high-velocity gas seemed chaotic, at least to the non-initiate. The publication of the Leiden–Dwingeloo Survey (Hartmann & Burton 1997), and the imminent completion of its southern extension with the radio telescope in Villa Elisa, Argentina, is a milestone for the study of neutral gas in the halo, as it provides a uniform dataset, with improved sensitivity and angular resolution. This progress is evident on comparing Wakker’s summary map of the HVC’s with the discovery map of the HI in the Magellanic Stream (Mathewson et al. 1974). The ambitious HIPASS project at Parkes is adding further sensitivity and resolution. My understanding of the results presented here is that a coherent picture is finally emerging in which (i) some HVC’s are connected to the HI in the Galactic disk, (ii) much of it is connected to the Magellanic Stream, with the beautiful HIPASS data of Putman et al. (1998) now also showing the leading arm predicted by numerical simulations of the encounter of the Magellanic Clouds with the Milky Way (e.g., Gardiner & Noguchi 1996; §1.3), and (iii) steady accretion of material either from the immediate surroundings of the Galaxy (as suggested by Oort 1970), or from within the Local Group.
(as advocated by Blitz at this meeting). Van Woerden and Wakker showed that absorption line studies and metallicity measurements are—at long last—starting to constrain the distances of individual clouds. Open issues include the possibility of hydrodynamic effects influencing the velocities (discussed by Benjamin and Danly), and the nature of the dense clumps seen in the HIPASS data.

Ionized halo gas remains elusive. Kalberla, Dettmar and Danly showed that X-rays and Hα emission indicate the presence of $10^6$ K gas to $|z| \sim 4$ kpc away from the disk. Maloney showed that the constraints on the total amount of this material remain rather weak, an issue to which I shall return in §2.4. The dispersion measures of pulsars in the LMC may help here, as discussed by Bailes, but the sample of objects is still small.

2. Dark Halo

The main topics discussed were the total mass and extent of the dark halo, the constraints on the mass of halo objects provided by microlensing experiments, and the nature of the dark matter.

2.1. Mass and Extent

Zaritsky summarized what we know about the mass of the Galaxy. The rotation curve is well established inside a galactocentric radius of 20 kpc, and constrains the mass profile fairly accurately. Outside this radius the main constraints are distances and radial velocities of the globular clusters, the dwarf satellites, and M31. A variety of methods and arguments show that all measurements to date are consistent with a model in which the mass distribution is essentially an isothermal sphere with a constant circular velocity $v_c \sim 180$ km/s. Out to a distance of $\sim 300$ kpc—nearly halfway to M31—this corresponds to a mass of about $2 \times 10^{12} M_\odot$. The average mass-to-light ratio is over 100 in solar units, so most of this matter is dark, or at least severely underluminous (§2.4).

The uncertainties in the halo mass profile remain significant, not only at the largest radii, but even inside the orbit of the LMC. This affects the determination of the mass fraction of MACHOs in the halo (§2.2). Substantial improvement will have to await better distances and in particular more accurate absolute proper motions for the distant globular clusters and satellites. This is not easy, as the required accuracy for Leo I and II is about 10 µas/yr (but see § 4). The derived space motions would leave only the nature of the orbits as uncertainty in the determination of the Galactic potential. The fact that some satellites and clusters may actually be on the same orbit is a complication.

2.2. Microlensing

Enormous effort world-wide is being put into microlensing studies of the Galactic Bulge, the LMC, and the SMC. Alcock summarized this in a public evening lecture. At the Symposium, he, Stubbs, and Perdereau gave more detailed status reports of the MACHO and EROS projects. The main triumph of these projects, derived from the 20 events seen to date towards the LMC, is that point-like objects in the mass range $10^{-7} \lesssim M/M_\odot \lesssim 10^{-2}$ can at most form a minor constituent of the halo, and hence do not form the bulk of the dark
matter that is tied to the Galaxy. This eliminates most objects of substellar mass, including planets as small as the Earth. Furthermore, the events seen towards the LMC have a fairly narrow duration distribution, which differs from that seen towards the Galactic Bulge. If these events are caused by halo objects, they must have masses in a rather narrow range around 0.5 $M_\odot$. Bennett showed how microlensing events which deviate from the standard lightcurve may be used to constrain the nature of the lenses further, and he reminded us that a major uncertainty is the unknown binary fraction in the lens population (e.g., DiStefano 1999).

The precise MACHO mass fraction of the halo is not easy to determine, not only because the number of observed events is still modest, but also because the halo mass distribution out to the distance of the LMC is not known very well (§2.1). It is possible that the MACHOs are not in the dark halo at all. Flaring of the disk and/or the warp of the Milky Way, or the presence of another intervening object have been considered, but it now seems unlikely that these can provide the entire set of observed events (e.g., Gyuk, Flynn & Evans 1999). Weinberg’s theoretical models of the LMC/MW interaction, and Olszewski’s analysis of the color-magnitude diagram of the LMC indicate that self-lensing by the LMC, in particular by its own stellar halo, may well be quite significant. Their results allow the possibility that all the lenses are in the LMC itself, as suggested already by Sahu (1994). This would require lens masses smaller than 0.5 $M_\odot$, which is plausible. However, if this is the explanation for the observed events, it then remains a puzzle why the duration distribution is different from that in the Bulge. The plans for the future outlined by Stubbs in the preceding talk address these issues in more detail.

A ‘byproduct’ of the microlensing surveys are massive homogeneous samples of variable stars in the LMC/SMC and also in the Bulge. These are a veritable gold mine for constraining stellar models, and for tracing Galactic structure. For example, Minniti showed that the RR Lyrae samples in the Bulge allow an accurate determination of the luminosity profile of the inner halo to very small galactocentric radii.

2.3. How many kinds of dark matter?

Turner presented his beautifully illustrated ‘Audit of the Universe’. This has seen considerable improvement in the past year driven by new observations. In particular, the distant supernovae projects (Schmidt et al. 1998; Perlmutter et al. 1999) indicate a non-zero cosmological constant $\Lambda$. Turner writes the total mass and energy density as $\Omega_0 = \Omega_M + \Omega_\Lambda$, and finds (to within factors of less than two, and in units of the critical density):

- $\Omega_{\text{lum}} \sim 0.003$ (observed)
- $\Omega_{\text{baryon}} \sim 0.03$ (Big Bang nucleosynthesis)
- $\Omega_M \sim 0.3$ (galaxy clusters)
- $\Omega_\Lambda \sim 0.66$ (supernovae)
- $\Omega_0 \sim 1.0$ (anisotropy of cosmic background radiation)

This means that while the baryon density $\Omega_{\text{baryon}}$ is ten times larger than the density of luminous matter $\Omega_{\text{lum}}$, it is still only ten percent of the total matter density of the Universe $\Omega_M$. The ‘dark energy’ $\Omega_\Lambda$ brings $\Omega_0$ to the critical
value within the uncertainties. As Turner pointed out, this state of affairs raises
a number of fascinating questions, two of which are most relevant for this confer-
ence. If $\Omega_{\text{baryon}}$ is in fact in galaxy halos, which is plausible given that $\Omega_{\text{galaxies}}$
is of the same order, then non-baryonic dark matter is needed at the scales of
clusters and larger in order to make up the difference between $\Omega_{\text{baryon}}$ and $\Omega_M$.
What is this material? If, on the other hand, we want only one kind of dark
matter on all scales (e.g., for reasons of simplicity), then the question becomes:
where are all the baryons? These questions lead directly to the issue of dark
matter composition, to which I now turn.

2.4. Composition

Many talks were devoted to the nature of the dark matter. With a few notable
exceptions, most speakers were more sure about what the dark mass is not
made of than about what it is, a conclusion also reached by Silk, who managed
to summarize most of these contributions on the first day of the conference, i.e.,
before they were presented!

Brown dwarfs. Tinney and Flynn reported on programs aimed at establishing
the number density of low-mass objects in the halo, using groundbased and
HST observations. The halo samples contain objects at a typical distance of 2
kpc, with a tail extending beyond 10 kpc. The observed mass functions extend
somewhat below 0.08 $M_\odot$, which marks the transition from stars to substellar
objects. The number density increases with decreasing mass, and perhaps turns
over at the lowest masses—in agreement with the microlensing results (§2.2). In
any case, smooth extrapolation of the measurements to lower masses shows that
these objects cannot provide all the dark mass in the Galactic halo. A caveat is
that the results are based on calibrations of local disk objects, which presumably
are more metal-rich than field halo objects.

Compact objects. Much work was done in the past two years to investigate
whether white dwarfs could be the major constituent of the dark halo. This
activity was triggered by the microlensing events seen towards the LMC, which
suggest a typical lens mass around 0.5 $M_\odot$, and the white dwarf nature of dark
matter was defended with great vigor by Chabrier. However, it seems that in
order to have white dwarfs in sufficiently large numbers requires a special initial
mass function early-on, i.e., a non-standard star formation history. This cannot
be ruled out a priori, but the resulting inevitable metal-enrichment is hard to
hide (Gibson & Mould 1997). Flynn showed that HST has not seen these white
dwarfs, but perhaps one needs to go even fainter. Goldman reported that a
proper motion survey being carried out by the EROS team will settle this issue
by providing a strong local constraint. Silk briefly discussed the possibility that
the dark halo consists mostly of neutron stars, and concluded that these suffer
from similar problems as the white dwarfs, and furthermore, their masses are
inconsistent with the microlensing results.

Cold gas. In the past few years, a number of authors have suggested that per-
haps the dark matter consists of ultracold (4K) clumps of $\text{H}_2$, with masses of
about $10^{-3}M_\odot$, diameters of 30 AU, and densities of $10^{10}$ cm$^{-3}$ (e.g., Pfenniger
et al. 1994; Gerhard & Silk 1996). The current microlensing experiments are
not sensitive to such clumps, as they are extended objects rather than effective
point masses. They have never been observed directly in the local interstellar
medium. There is strong disagreement on the presumed location of this material. Pfenniger suggested that this dark matter is in a large outer disk, while Walker proposed that it is in a spheroidal halo. This latter suggestion has the advantage that the ionized and evaporating outer envelopes of these clumps could be responsible for the so-called extreme scattering events seen in radio observations (Fiedler et al. 1987). While Chary reported that the expected cosmic-ray induced gamma rays are not seen, recent work by Dixon et al. (1998) suggests that they are evident in the EGRET data.

**Ionized Gas.** Kahn & Woltjer (1959) established the mass of the Milky Way and M31 through their famous timing argument, and suggested that most of the unseen mass could be ionized gas of about $10^6$ K, which is very hard to detect. Maloney summarized the best observational constraints on the total amount of such gas, and showed that the limits are no stronger than they were 40 years ago. Kalberla showed recent ROSAT evidence for such gas, and derived a scale-height of about 4 kpc. The very sensitive Hα surveys that are now possible with TAURUS-2 (Bland–Hawthorn et al. 1998) and with the WHAM camera (Tufte et al. 1998) should allow a measurement of the total amount of ionized gas in the near future. This may be the best bet for baryonic dark matter attached to the Galaxy (cf. Fukugita, Hogan & Peebles 1998).

**Nonbaryonic dark matter.** All of the above candidates for the dark matter are baryonic. Assuming Turner’s audit is correct, this can make up only 10% of the total amount of matter in the Universe. It is natural to assume that this material is associated with galaxies. The remaining 90% of the mass in the Universe (the difference between $\Omega_{\text{baryon}}$ and $\Omega_M$) then has to be made up of non-baryonic material. Sadoulet, Silk and Turner discussed the candidates, which include massive neutrinos, axions and neutralinos. It seems unlikely that the neutrinos provide all the unseen mass on large scales, because (i) they would not constitute the cold dark matter that is currently favored by theories of structure formation, and (ii) the required neutrino mass of $\sim 25$ eV seems to be ruled out by experiments. To date, there is no experimental evidence for axions or neutralinos, but the laboratory sensitivity is expected to improve considerably in the coming year. And finally, Silk argued that perhaps primordial black holes are the culprit, a most fascinating suggestion.

3. Other Galaxies

Surface photometry of edge-on disk galaxies to $V \sim 28$ mag/arcsec$^2$ by Morrison and by Yock shows that these systems display a variety of luminosity profiles perpendicular to the disk. This may indicate an outer bulge, a thick disk, or perhaps a luminous stellar halo. It will be very interesting to try to go to fainter limiting magnitudes, and to enlarge the sample to search for correlations with e.g., Hubble type. Determination of the mass distribution in other disk galaxies is based mostly on HI rotation curves, and gives strong evidence for extended halos of dark matter, consistent with the findings for our own Galaxy. Unfortunately, Kalnajs fell ill, and was unable to present his views on this topic. Bland–Hawthorn showed convincing evidence that Hα measurements can now probe the mass distribution beyond the HI edge, even though the effort required can only be described as heroic.
The luminous halos of galaxies in the Local Group can be studied in more detail. Sarajedini showed color-magnitude diagrams for ten globular clusters in M33, obtained with HST. While some of these clusters have the same age as the Galactic globular clusters, and are just as metal-poor, others are several Gyr younger, and have intermediate metallicities, indicating a more extended halo formation process. Freeman showed that M31 is very similar to the Milky Way, albeit a little more massive and with a larger bulge. The kinematics, abundances, and ages of the M31 globular clusters are very similar to those in the Milky Way, suggesting they must also have formed quickly. However, the field stars in the M31 halo are decidedly more metal-rich than those in the Galaxy. It is not clear how this comes about, especially since a significant fraction of the halo field stars must have been tidally dislodged from clusters. The kinematics of the M31 field halo stars should contain further clues to their formation, and can now be studied in detail through the set of over 1000 planetary nebulae for which radial velocities have been measured. Still closer in, Da Costa and Olszewski showed that satellite dwarf spheroidals and the Magellanic Clouds all have experienced different star formation histories, as is evident from the beautiful variety of color-magnitude diagrams. With the possible exception of the SMC, the oldest populations invariably have the same age as the Galactic globular clusters. Clearly, around 12–14 Gyr ago the first generation of stars was formed synchronously throughout the entire Local Group.

4. Observational prospects: towards a stereoscopic census

The currently popular formation scenario was summarized by Wyse and by White. It assumes a hierarchical build-up of structure in a cold dark matter universe, with the baryons collecting inside dark halos, and forming disks. Elliptical galaxies and bulges then result from major mergers, while disk galaxies remain disks only as long as they steadily accrete no more than small satellites (e.g., Baugh, Cole & Frenk 1996). This scenario then suggests there should be signs of ongoing accretion and fossil substructure in the Galactic halo, as is indeed observed. The next step is to test this formation scenario quantitatively through a detailed comparison with the observed properties of the Galaxy, and notably its halo. This is a crucial complement to high-redshift studies of galaxy formation, and should provide the detailed formation history of our Galaxy.

The theoretical tools to analyse halo substructure that are now being developed (e.g., Helmi & White 1999) demonstrate the need for accurate kinematic data for large samples of halo objects. The ongoing Hamburg/ESO objective prism survey, outlined in a poster by Christlieb, covers 10000 square degrees and promises to extend the HK Survey (§1.1) to about 20000 candidate halo objects. Multi-object spectroscopy by 2DF or SLOAN will provide radial velocities and abundances (see poster by Pier). The HIPPARCOS Catalog contains globally accurate proper motions with accuracies of ~1 mas/yr for a few hundred bright and nearby halo stars. Combination of the Tycho positions for nearly 3 million stars to V~12 with those in the Astrographic Catalog, which are each of modest individual accuracy but have an epoch difference of about 80 years, will provide proper motions of 2–3 mas/yr (Hoeg et al. 1998). The resulting TRC/ACT database will contain about 30000 halo stars, and should be available in a year
or two. As 2 mas/yr translates to 10 km/s at 1 kpc, this will allow space motions to be derived for halo stars out to distances of a few kpc. The USNO-B Catalog reaches about five magnitudes fainter, and can be put on the HIPPARCOS/Tycho reference system, but the accuracies of individual proper motions will be only $\sim 8$ mas/yr (Monet 1997), making them of modest value for the study of the Galactic halo.

The success of HIPPARCOS has resulted in further interest in space astrometry, leading to the ongoing ESA study of a mission-concept called GAIA (e.g., Gilmore et al. 1998). Interest in imaging terrestrial extrasolar planets is pushing NASA’s Space Interferometry Mission. SIM will be a pointed observatory, and will provide proper motions and parallaxes of micro-arcsecond ($\mu$as) accuracy by the end of the next decade. If approved, GAIA will provide parallaxes and absolute proper motions of similar quality for all the one billion stars to $V \sim 20$, together with radial velocities and photometry or low-resolution spectroscopy for most objects brighter than $V \sim 17$, by 2015. This is a long time, but the tremendous gain over HIPPARCOS, summarized below, will be worth the wait.

### Comparison of HIPPARCOS and GAIA

|                        | HIPPARCOS | GAIA       |
|------------------------|-----------|------------|
| Magnitude limit        | $\sim 12$ | $V = 21$   |
| Completeness           | 7.3–9.0   | $V = 20$   |
| Number of objects      | $1.2 \times 10^5$ | $1.2 \times 10^9$ |
| Accuracy               | 1–2 mas   | $4 \mu$as  |
|                        |           | $(V < 10)$ |
|                        |           | $10 \mu$as |
|                        |           | $(V = 15)$ |
|                        |           | $0.2 \mu$as|
|                        |           | $(V = 20)$ |
| Radial velocities      | –         | 3–10 km/s  |
| or low-resolution spectroscopy | –     | $(V < 16–17)$ |
|                        |           | multi-color |
|                        |           | $(V < 16–17)$ |
|                        |           | $R=20–40\text{Å}$ |
|                        |           | $(V < 17–18)$ |

This is not the place to summarize the entire scientific rationale for $\mu$as astrometry from space, and its impact on all aspects of the structure of the Galaxy, stellar physics, detection of planets around other stars, etc. The relevance for the study of the Galactic halo is best illustrated by considering the mind-boggling accuracy of the SIM and GAIA proper motions: an uncertainty of $10\mu$as/yr translates to 5 km/s at 100 kpc! This will make it possible to measure the space motions of globular clusters and all the dwarf satellites, including Leo I and II. The unbiased coverage of the entire sky by GAIA will allow identification of very large halo samples from the narrow-band photometry, and provide measurements of the full six-dimensional phase space information (positions and velocities) throughout the inner halo (to distances of about 20 kpc from the Sun), and full velocity information on individual stars to much larger distances. This will e.g., (i) provide the mass distribution of the Galaxy with unprecedented accuracy, (ii) allow kinematical selection of the members of the globular clusters and dwarf satellites, leading to clean color-magnitude diagrams, and (iii) trace ghostly streams and substructure. High-resolution spectroscopic follow-up will provide the distribution of the abundances throughout the halo. This will allow reconstruction of the full formation history of the Galaxy.
5. Concluding remarks

This Symposium is dedicated to Alex Rodgers. Alex was well-ahead of the field with his early work on metal-rich halo stars (Rodgers, Harding & Sadler 1981), and his investigation on retrograde globular cluster orbits (Rodgers & Paltoglou 1984), both of which indicated the presence of infall and substructure. He would clearly have enjoyed this meeting. The string of three successful and stimulating international Stromlo Symposia have established the series, and are a credit to Australian astronomy. We are all looking forward to number four!

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