AUXILIARY OBSERVATIONS RELATED TO A FUTURE SPACE ASTROMETRY MISSION: SUMMARY OF THE PARALLEL DISCUSSION SESSION

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1. ASTROPHYSICS FROM ASTROMETRY: WHAT ELSE IS NEEDED?

An essential prerequisite for any serious observational study of the Galaxy and of its contents, and of the available Local Group galaxies, especially the Magellanic Clouds, is that some relevant parameters of a fair sample of the typical contents be measured. Since the Milky Way is a late-ish type spiral, and since the Sun lies very close to the Galactic Plane, most of the stars in the Galaxy, and almost all of the interesting dynamics, are found at low Galactic latitudes. A cone of radius 30° centred on the Galactic centre contains about one-half of the stars in the Galaxy, most of the star formation regions, most of the young stars, most of the high stellar density regions, most of the highly evolved asymptotic giant branch stars, all of a dynamical bar, if such a thing exists, most important Galactic dynamical resonances, much of the spiral structure, most of the molecular material, all of the Bulge, most of the disk, and so on.

When looking along such lines of sight one rapidly encounters crowded fields, obscured by dust. Thus, there is an overwhelming scientific requirement for any survey which aspires to study a large fraction of the volume of the Galaxy to operate at faint limiting magnitudes, probably in the near infrared, in very crowded fields, and where no blue-uv data are likely to be obtainable. A mission with astrometric performance similar to that expected for GAIA, operating with these parameters, would completely revolutionize our knowledge of stellar kinematics and Galactic structure, in both the Milky Way and in its neighbour satellite galaxies.

Presuming such a mission to exist, one then asks *'What additional information is essential to realise the astrophysical potential?'*. This question may best be addressed by considering in very broad terms the relationships between astrophysics and observations.

The important conclusion of this inter-relationship is that the physics of galaxy evolution cannot be taken as a series of independent questions: a galaxy is a non-linear combination of many coupled physical processes which can be understood only by many complementary approaches. Similarly, it is clear that *ab initio* predictive calculations *in isolation* can play only a minor role in the understanding of galaxies of the type in which we live, compared to that which could be provided by the combination of a substantial observational survey together with a sophisticated program of astrophysical analysis.

The aim of the discussion session was to identify those auxiliary observations which are on the critical path between a GAIA-like survey and substantial astrophysics.

The implication of the inter-relationship of many types of observation and many aspects of physical analysis is that complementary yet inter-locked investigations of all major aspects of galactic structure are required for significantly improved understanding. It is this coordinated complementarity of sophisticated analysis, together with suitable statistically valid observational studies, that is currently unachievable, but which can be achieved by extending kinematic and photometric studies to the whole of the Milky Way Galaxy, and its neighbours.

The discussion began with the outline below. The table illustrates the three major types of observations, their analysis, and the dominant physical processes they illuminate; SFR indicates Star Formation Rate, IMF (stellar) Initial Mass Function, and ISM Interstellar Medium:

Type of Data		*Model Function*		*Physics*
Kinematics	$\Longleftrightarrow$	Dynamics	$\Rightarrow$	
radial velocities proper motions		phase space distribution function spatial distributions		gravitational potential dissipational history
Chemical Abundances	$\Longleftrightarrow$	Chemical Evolution	$\Rightarrow$	
line strengths, photometry		star formation history ISM history		stellar initial mass function gas flows, dissipation, SFR
Luminosity Profiles	$\Longleftrightarrow$	Galactic Structure	$\Rightarrow$	
colour–magnitude data surface brightness		spatial distribution function luminosity functions		stellar IMF, binarity, dissipation, SFR, ...

2. RADIAL VELOCITIES

It is clear from this summary, from the very extensive discussions resulting from it, and from the considerable community experience in analysis of extant astrometric data, that there is one self-evident additional requirement for optimal astrophysics, namely the additional component of space motion. Thus, RADIAL VELOCITIES are the highest scientific priority additional requirement. The scientific requirement here is clear: it is not possible in principle to deduce statistically the missing component of space motion. This follows since the orientation of the velocity ellipsoid, and hence the amplitude of the projected components of space motion, is determined by the local gravitational field gradients. As a rule of thumb, the velocity ellipsoid will be aligned with that coordinate system in which the local gravitational field is separable. Since it is usually determination of that gradient, and that coordinate system, and its local variations, which is the goal of the astrophysical analysis, it cannot be assumed. For example, one may be interested in weighing spiral structure. Such an analysis requires full orbital dynamics, and cannot assume them.

The timing and precision of the necessary radial velocity data are also quantifiable. One might imagine that a precision comparable to that attainable with the tranverse velocities would be desirable, but this is not so. Careful analyses (Wielen, this meeting; Hargreaves, Gilmore & Annan 1995 MNRAS in press) show that there is an irreducible uncertainty of about 1 km/s in the time-averaged mean velocity of any star, determined by the possible presence of unidentified binarity, with period greater than about 100 years. Such binarity could not be identified during the lifetime of GAIA. Thus, two requirements arise: radial velocities must be obtained, with many repeat measurements, for the several years of the GAIA mission, to provide both a mean velocity and an identification of short period binarity. [Such a survey in itself is of course of immense scientific interest.] Secondly, a natural minimum precision for such radial velocity determinations, on astrophysical grounds, is about 1 km/s. Thus spectra are required.

For a mission with the precision of GAIA a third quantifiable requirement is identifiable. Variations in the radial velocity of a stellar system, due primarily to binarity, will be a significant contributor to the measured astrometry. Thus, it is necessary that radial velocity orbits be known with a precision in phase such that the radial velocity for every star observed by GAIA is known *at the time of the GAIA observation.* This is an extreme requirement for any ground-based radial velocity programme, and argues, very strongly, that acquisition of radial velocities with a precision of about 1 km/s *by the spacecraft* should be a requirement for the GAIA mission. We note that the time-coincidence requirements for the radial velocity determinations are not so extreme as for the photometry, discussed below. Thus, an additional telescope on-board, dedicated to radial velocity measurements, need not necessarily be aligned with the direction of the astrometric telescopes.

3. PHOTOMETRY

It is manifestly essential that one has some information on the astrophysical type of the object of study. Some part of this is required in advance, as an input catalogue. Since many stars are photometric variables, and in many cases may have time-dependent kinematics which are correlated with their photometry—e.g., pulsating variable stars—photometry coincident with the astrometric measurements is essential to optimise the scientific return. This is well illustrated by the vast scientific return of the TYCHO mission aboard Hipparcos, and by the outcomes of the several gravitational micro-lensing surveys. These latter in particular have discovered of order 100 microlensing events, but have derived many tens of thousands of light curves of field variables. The scientific return from those programmes looks certain to be dominated by their contribution to Galactic structure and to stellar evolution... Of course, photometry coincident with astrometry can be achieved if and only if the photometry is obtained on board the astrometric spacecraft.

In addition to the temporal photometry, accurate determination of reddening, stellar temperature, circumstellar properties, and so on, requires photometry over the widest possible wavelength baseline. It is worth noting explicitely that the need for photometry could in principle be met from the spectrophotometry which is to be obtained for radial velocity determinations. However this would be possible in practice only if that spectrophotometry covers a very wide wavelength range. Such a range will be very much wider than is required just for radial velocities, and may well be inherently incompatible with the high dispersion required for precise radial velocity measurements, given a detector of realistic size. Thus, it is almost certainly more cost-effective, and more consistent with the scientific drivers, to have a photometric system, with a very wide wavelength range, as well as a spectrophotometric system covering a relatively narrow wavelength range at sufficiently high dispersion to ensure good radial velocities.

4. STELLAR ELEMENTAL ABUNDANCES

Chemical abundances are the next most significant astrophysical datum after kinematics and distances. In spite of the desirability of such information with a precision—of order 0.05 dex—comparable to intrinsic cosmic dispersion, it is clear that such data are desirable rather than essential for analysis of the primary astrometric data. The main argument here is that the abundance dependence of distance, when derived indirectly for stars without accurate GAIA parallax distances, e.g. for multicolour photometry, can be calibrated accurately from the main GAIA data set. There are two main reasons for this conclusion: most importantly, recent very high precision analyses suggest that the true scatter in the *relative* distribution of the elements is very small, for stars with a given Galactic orbit. Thus, a relatively small number of stars need to be studied in detail to quantify the systematic trends in chemical evolution. Such a project can be efficiently carried out from extant ground-based facilities, albeit not easily. Additionally, high precision photometric and spectrophotometric data are required for such a study. The acquisition and analysis of such data is a prohibitive task, one where the scientific goals are not obviously in proportion to the required cost.

5. DATA PROCESSING REQUIREMENTS

A mission which is to produce 50 million spectra presupposes automated spectral reduction and measurement. Considerable efforts along these lines are underway for application to the forthcoming redshift surveys, which will produce of order one million spectra. There are several promising approaches, one example discussed in some detail being Artificial Neural Networks (ANNs). ANNs may be de-mystified by considering special cases which generalize other statistical methods common in astronomy and other fields. In particular, ANNs generalise Bayesian methods, multi-parameter fitting, principal component analysis, Wiener filtering and regularisation methods. Examples of morphological classification of galaxies were presented at the meeting to illustrate how non-linear ANNs improve on linear techniques. Similar methods can be applied to automated classification of galaxy and stellar spectra. Further explanations may be found in a special issue of *Vistas in Astronomy*, Vol. 38, No. 3, 1994.

The important conclusion for the GAIA mission is that, although automated classification and analysis software will be a critical requirement for the scientific success of the mission, the rapid current progress in applying such techniques to similar data induces confidence that the analysis will be feasible when required.

6. GAIA AND GALAXIES

Although one tends to think of point sources for astrometric studies, it must be realised that the photometric and spectroscopic data obtained by GAIA will constitute an all-sky flux-limited catalogue. GAIA will, as a free bye-product, generate a catalogue of galaxies which vastly exceeds in quality, uniformity, areal coverage and completeness any which exist or are planned today. Additionally, redshifts will be derived for a large subset of these. The scientific return from a survey of this type is immense, and should not be overlooked!

7. ARCHIVES AND LATER USES OF THE DATA

An interesting consequence of a project, such as GAIA, which will produce substantially more uniform-quality data than the total currently in existence, is that it defines its own reference set. That is, the spectra and photometry provided by GAIA, being for stars with superb distances, and hence absolute luminosities, will supercede any extant calibration and classification systems. While this provides the freedom to design the GAIA photometric system from first principles, in the light of topical understanding of the HR diagram, it also imposes a requirement. Any standard must be available as a comparison for future use, as a database for future refinement, and as a template for application. Additionally, it is the almost inevitable experience of any observational survey on this scale, that iterations in the database refine and improve the first approximation to the classification scheme. Certainly, with a survey on this scale, increasing degrees of complexity and sophistication will become apparent when the full database is available for careful analysis. Thus, it is a requirement for efficiency that the data base be maintained in an accessible form, with this accessibility continuing after the in-orbit mission lifetime.

8. INPUT CATALOGUES

The final essential auxiliary observation is that which will be required first—an input catalogue. Over most of the surface area of the sky the star density is low, reddening is minimal, and the problem is under control. The solution is probably the GSCII, described by Lasker etal at this meeting. However, it must be remembered that the average star is not at the average place in the sky. The average star lies in crowded, reddened, fields. If one weights further by scientific case, then most of the astrophysical interest for GAIA is at low Galactic latitudes, and is reddened. In such fields Schmidt plates, with their several arcsec resolution, and visual sensitivity limits, are not suitable. In order to provide a source list which is both reliable, remembering the crowding, and astrophysically interesting, remembering the reddening, both substantially higher spatial resolution and a redder survey wavelength are required, with a linear detector. The Galactic latitude at which one must switch from the Schmidt plate surveys is not yet quantified, but is probably about 15°, rather more near the Galactic bulge and the other Local Group galaxies, and near star clusters.

Digital 1–2μm surveys are underway (DENIS, 2MASS), which in principle prove the viability of such techniques. Rather deeper surveys will be required for GAIA, however. Detailed investigation of the means to provide such survey information is one of the most urgent requirements for the scientific success of the GAIA mission.

9. SUMMARY

The complementary information required to ensure an outstanding astrophysical success for a GAIA-like mission can be quantified quite accurately. Since the aim of GAIA is to provide precision kinematics and distances for stars across the Galaxy, it must be able to see stars that far away. This necessarily requires observations in the galactic plane, in crowded and obscured fields. Thus, an immediate requirement is an input catalogue, based on linear digital detectors, with arcsecond or better spatial sampling, covering the galactic plane. There are substantial scientific benefits in biassing such a survey, and the GAIA mission itself, to the near infrared.

When one has astrometry, the primary additional requirements to achieve astrophysics are clear: one requires the additional component of space motion—i.e., radial velocities. There are considerable scientific and practical benefits in acquisition of such radial velocity data by parallel observations made with the GAIA spacecraft.

Given kinematics and distances, one requires some information to classify the astrophysical type of the object of study. This latter includes an absolute minimum requirement of photometry, which must be obtained at the same time as are the astrometric measurements. Thus, an onboard photometric facility is essential. Additional desirable information, which is however not essential, includes spectrophotometry, spectral types, binarity, chemical element abundances, foreground reddening, and so on.

Both the radial velocity and photometry scientific requirements would be met most effectively by observations made from the same spacecraft platform as GAIA, complemented by a suitable input catalogue. Some automated classification system will be essential to process such large databases, as will provision for a suitable archival facility. Recent developments in artificial classification systems for astrophysical applications suggest this requirement will be met. It should also be remembered that the auxiliary photometry and spectroscopy proposed here for the GAIA mission will generate the largest and most complete photometric and redshift survey of galaxies available, with immense scientific importance.