ESF Workshop: Modelling the Galaxy in the Era of Gaia

Executive Summary

Gaia is a Cornerstone Mission of the European Space Agency (ESA) that is scheduled for launch in late 2011. It will obtain astrometric quantities (angular position, parallax, and proper motion) and photometry in many wavebands for $\sim 10^9$ stars, and spectra for $\sim 10^7$ stars. The core scientific programme for which these data are being gathered is to determine the structure of our galaxy (including the distribution within it of dark matter) and the manner of its formation. The key results will emerge by comparing the predictions of dynamical Galaxy models to the data.

The science of building dynamical Galaxy models is still in its infancy, and must be pushed forward energetically if satisfactory models are to be available when the first data arrive. Moreover, major ground-based surveys are either in hand (RAVE, SEGUE) or recently completed (2MASS, 2dF, DENNIS) that can only be properly exploited by comparison with predictions from sophisticated dynamical models.

From 6–9 September 2005 28 dynamicists, all but one from a European institution, met in Oxford to review the current situation, and to consider how to move forward. A programme of collaborative work, and a strategy for obtaining funding for this work was agreed.

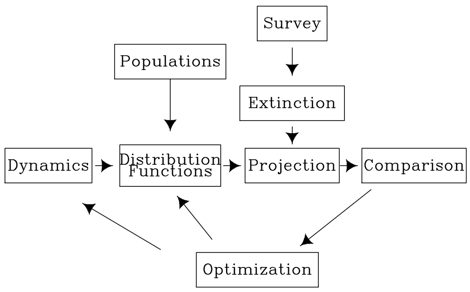

Figure 1. Schematic breakdown of software

Work packages
Figure 1 shows the agreed breakdown of the work to be done into packages that are broadly aligned with self-standing units of software. Details of the individual packages and which participants wished to be involved with them are given in the Appendix.

Future Development
Funding for software development will be sought within the framework of the Virtual Observatory. Some workshop participants were members of the VEGA consortium that is making the UK's contribution to the Virtual Observatory, and they would seek to make Galaxy modelling a part of the VEGA programme.

It was recognized that the bulk of the funding of the work would have to come from national research councils. Several centres had already secured funding for Galaxy-modelling work, and some applications are pending. In the UK the Science Committee of PPARC had acknowledged that significant resources would need to be invested in modelling work if GAIA's goals are to be achieved. The existence of a European framework for the programme would undoubtedly add weight to applications to national research councils.

An application for an EU Research & Training Network was submitted in the weeks following the workshop.

The Gaia Data Analysis Coordination Committee has been asked to accord the workshop participants official status, perhaps within the framework of Coordination Unit 7, "Catalogue access and scientific exploration".

Webpages that include a wiki have been set up to facilitate exchanges of documents. The collaboration plans to hold a second meeting in about a year.

Appendix: Details of work packages

The Dynamics module contains the equations of motion and essentially produces orbits. Different groups within the workshop planned to produce versions that employed (i) the Made to Measure technique of Syer & Tremaine [1,2], (ii) the extended Schwarzschild technique, and (iii) the Torus technique [3,4,5].

The DF module is responsible for populating orbits. It is driven by the Populations module, which specifies the populations that make up the Galaxy. A population is to be understood as a group of stars with a specified history and chemistry. It might be quite inhomogeneous as in the "thin disk", in which both epoch of birth and chemistry vary significantly, or it might be very homogeneous, as in "metal-poor BHB stars"; the breakdown into populations is driven by astrophysics, and may be simple or complex. Once a population has been specified, its luminosity function in each waveband will follow from population-synthesis models, and its distribution over orbits is likely to be restricted by a mix or morphological and dynamical constraints. For example, the "thin disk" would have a distribution function that peaked on circular orbits and broadened in action space around these orbits with stellar age, to reflect the stochastic heating of the disk. The DF of the BHB stars, by contrast, would depend only weakly on L_z at fixed energy.

The Projection module is responsible for producing observed quantities from the dynamical model. It receives the luminosity functions from the Population module, an extinction model from the Extinction module, and the survey parameters, such as colour selection, magnitude limit, and observational errors from the Survey module. On the basis of these inputs it produces either (a) a mock catalogue in $(l, b, \varpi, \mu_x, \mu_y, v_{\rm los})$ space, or (b) probability densities in this space. When appropriate, the module would produce corresponding predictions of microlensing observables (probability densities of events of each duration for source stars of given magnitude).

The Comparison module assesses the quality of the fit between data and the model predictions by integrating through observable space the error Gaussian of each catalogue star times the model density (which in the case of a mock catalogue would be just a sum of delta functions).

The Optimization module would maximize the quality of fit returned by the Comparison module by adjusting the parameters in the DF module. In principle it would also adjust the potential used in the Dynamics module, but in practice this adjustment might not be automatic.

Table 1 shows which participants hope to contribute to the development of the various modules.

Table 1. Who does what

Dynamics	Choice of Φ	Binney, Bienaymé, Zhao
	M2M	Dehnen, Kroupa, Magorrian, Zhao, Gerhard?
	Schwarzschild	Cappellari, Patsis
	Tori	Binney, Cappellari, Dehnen, Famaey, Helmi, Kaasalainen, Siebert, Wilkinson
Local Cosmos	Aguilar, Eke, Dehnen, Helmi, Ibata?, Kroupa, Zhao	
Populations & DFs	Binney, Bienaymé, Cappellari, Famaey, Kerins, Flynn, Gerhard, Kroupa, Robin, Wilkinson	
Projection & extinction	Aguilar, Binney, Bienaymé, Brown, Robin	
Comparison & Optimization	Binney, Cappellari, Dehnen, Dejonghe, Kaasalainen, Kerins, Wilkinson	
Webpages	Kerins, Magorrian, Siebert	

Virtual Observatory

It would clearly be of great value to astronomers if the Virtual Observatory were able to deliver for specified selection criteria mock catalogues of Galactic objects expected in any given field. Consequently, the modelling machinery would be of value as an input to the Virtual Observatory, and it was agreed that the projection module should be able to produce output that is appropriately formatted.

Substructure
The apparatus just described concentrates on the production of smooth Galaxy models. At the workshop there was much discussion of the importance and diagnostic power of substructure, such a tidal streams and moving groups. Smooth models have a valuable role to play in revealing such structures, through the phase-space analogue of unsharp-masking: when an accurate smooth model is subtracted from the data, substructure will stand out more prominently. Moreover, action-angle variables, which are a byproduct of the torus modelling programme, make it possible (a) to project the data into a lower-dimensional space in which tidal streams should be prominent, and (b) to perform accurate perturbation theory, which promises accurate models of the moving groups that are generated by spiral arms and the bar.

The local cosmos
The workshop considered the role that simulations of cosmological structure formation might play. It does not seem likely that by brute force alone these simulations can be brought to the level of resolution that is required for much Galaxy modelling work. The problem is that low-luminosity stars play a significant role in the solar neighbourhood, and are completely invisible at 10-kpc distances, with the consequence that a sampling of the luminosity function that is deep enough to provide an adequate model of the solar neighbourhood, causes nearly all the simulation's stars, which lie at 10-kpc distances or greater, to be invisible.

One possible resolution of this difficulty, is to dither nearby stars into numerous copies. Another is to subject a torus-based model to the fluctuating gravitational field inferred from a cosmological simulation, and to use canonical perturbation theory to follow the dynamics of the initially smooth model.

References

1. Syer, D. & Tremaine, S., 1996, MNRAS, 282, 223
2. Bissantz, N., Debattista, V.P. & Gerhard, O., 2004, ApJ, 601, 155
3. Kaasalainen, M., 1994, MNRAS, 268, 1041
4. Kaasalainen, M. & Binney, J., 1995, Phys. Rev. Lett., 73, 2377
5. Dehnen, W. & Binney, J., 1996, astro-ph/9601040

ESF Exploratory Workshop

Modelling the Galaxy
Final Workshop Programme

September 6

9.00 - 9.15 Welcome by Rene Kamermans on behalf of the ESF
9.15 - 9.35 What do we hope to accomplish? (Binney)

Session 1: Data sources - potential & problems

(Input Data: Characteristics of ground-based data available in near term & later in GAIA catalogue)

09.35 - 10.05 Photometric & proper-motion surveys (Rix)
10.05 - 10.30 Spectroscopic surveys (Siebert)
10.30 - 10.55 Parallax surveys (Brown)

11.15 - 12.30 Microlensing surveys (Kerins, Smith)
12.30 - 12.45 Discussion of surveys

Session 2: Dynamical Models I

15.00 - 15.30 Population models (Robin) (Colours as a function of metalllicity \& age; Populations required - their likely initial orbits & orbit evolution)
15.30 - 17.15 Tidal streams: how to model them & what they teach us (Helmi, Dehnen, Zhao)

September 7

Session 3: Dynamical models II

09.00 - 09.45 Made-to-measure N-body simulations (Magorian)
09.45 - 10.30 Schwarzschild modelling (Cappellari, Rix)
10.30 - 11.00 Dynamical models with quadratic programing (Dejonghe)

11.15 - 12.30 Torus modelling (Binney, Kaasalainen)
12.30 - 12.45 Characterization of models (importance of availability of distribution functions or similar)

14.00 Tour of Old Library \& College for Group 1

Session 4: Dynamical models III

15.00 - 16.00 Hydrodynamical models (Eke)
16.15 - 17.00 Discussion of modelling strategies

Workshop Dinner (Saville Room 7.00 for 7.30)

September 8

Session 5: Confronting the data

09.00 - 10.00 Building a mock catalogue (Robin, Kerins)
10.00 - 10.30 Detecting fine structure with GAIA (Aguilar)
10.30 - 11.00 Automatic classification in the RAVE and SDSS data sets (Evans)

11.15 - 11.45 Marginalizing over DFs (Magorrian)
11.45 - 12.15 Fitting proper motion and radial velocity distributions with a simple dynamical model (Bienayme)
12.15 - 12.45 Disk heating through cluster star formation (Kroupa)

14.00 Tour of Old Library \& College for Group 2

15.00 - 15.30 Building the Halo (Flynn)
15.30 - 15.45 Matching potential, DFs, and phase-space samples: a special kind of inverse problem (Kaasalainen)
15.45 - 16.00 Discussion of techniques for interfacing models to data

Session 6: Strategies for improving the fit

16.15 - 16.45 Is automated optimization of a complete model feasible? (Wilkinson)
16.45 - 17.00 Are there useful minimal models?

September 9

Session 6: Software components

09.00 - 09.30 Can we identify common-use tools and shared products?
09.30 - 10.00 Should we connect with the Virtual Observatory?
10.30 - 11.00 Can we agree useful interface standards?

11.15 - 13.00 Who does what?

Session 7: How do we get the work funded?

14.0 - 15.00 Is there scope for joint approaches to: national research councils / ESA / EU

List of attendees

Name: Prof Luis A. Aguilar
Affiliation: National University of Mexico
Address: Apdo. Postal #877
22800 Ensenada, B.C.
MEXICO
E-mail: aguilar@astrosen.unam.mx

Name: Prof Olivier Bienayme
Affiliation: Strasbourg Observatory
Address: 11 rue de l'universite
F-67000 Strasbourg
France
E-mail: bienayme@pleiades2.u-strasbg.fr

Name: Dr Anthony Brown
Affiliation: Leiden University
Address: Sterrewacht Leiden, Postbus 9513, Leiden 2300RA, The Netherlands
Email: brown@strw.leidenuniv.nl
Phone: +31 71 275835; Fax: +31 71 275819

Name: Prof James Binney
Affiliation: Oxford University
Address: Rudolf Peierls Centre, Keble Road, Oxford OX1 3NP, UK
E-mail: binney@thphys.ox.ac.uk

Name: Dr Michele Cappellari
Affiliation: Leiden Observatory
Address: P.O. Box 9513
2300 RA Leiden
The Netherlands
E-mail: cappellari@strw.leidenuniv.nl

Name: Dr Walter Dehnen
Affiliation: Leicester
Address: Department of Physics & Astronomy,
University of Leicester,
University Road
Leicester, LE1 1RH
E-mail: wd11@astro.le.ac.uk

Name: Prof Herwig Dejonghe
Affiliation: Sterrenkundig Observatorium, UGent
Address: Krijgslaan 281, S9, B9000 Gent
E-mail: Herwig.Dejonghe@UGent.be

Name: Dr V.R. Eke
Affiliation: Durham University
Address: Department of Physics, University of Durham, South Road, Durham DH1 3LE
E-mail: v.r.eke@durham.ac.uk

Name: Dr N.W. Evans
Affiliation: Cambridge
Address: Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
E-mail: nwe@ast.cam.ac.uk

Name: Dr Benoit Famaey
Affiliation: Oxford University - Universite Libre de Bruxelles
Address: Rudolf Peierls Centre, Keble Rad, Oxford OX1 3NP, UK
E-mail: bfamaey@astro.ulb.ac.be

Name: Dr Chris Flynn
Affiliation: Tuorla Observatory
Address: Tuorla Observatory, Piikkio, FI-21500, Finland
E-mail: cflynn@utu.fi

Name: Prof Amina Helmi
Affiliation: Kapteyn Astronomical Institute
Address: P.O. Box 800, 9700 AV Groningen, The Netherlands
E-mail: ahelmi@astro.rug.nl

Name: Dr Mikko Kaasalainen
Affiliation: Department of Mathematics and Statistics, Univ. of Helsinki
Address: Department of Mathematics and Statistics, P.O.Box 68,
00014 Univ. of Helsinki, Finland
E-mail: mjk@rni.helsinki.fi

Name: Prof Rene Kamermans (ESF Representative)
Affiliation: Utrecht University
Address:
E-mail: R.Kamermans@phys.uu.nl

Name: Dr David Katz,
Affiliation Observatoire de Paris
Address: Observatoire de Paris - GEPI
5 Place Jules Janssen - 92195 Meudon Cede
E-mail: david.katz@obspm.fr

Name: Eamonn Kerins
Affiliation: Liverpool John Moores University
Address: Astrophysics Research Institute, 12 Quays House, Egerton Wharf,
Birkenhead, Merseyside CH41 1LD
E-mail: ejk@astro.livjm.ac.uk

Name: Mr Rainer Klement
Affiliation: Max-Planck Society
Address: Max-Planck Institut fuer Astronomie, Konigstuhl 17,
Heidelberg, 69117, Germany
E-mail: rix@mpia.de

Name: Prof Pavel Kroupa
Affiliation: Sternwarte, University of Bonn
Address: Auf dem Huegel 71, D-53121 Bonn, Germany
E-mail: pavel@astro.uni-bonn.de

Name: Mr Teemu Laakso,
Affiliation: Department of Mathematics and Statistics, Univ. of Helsinki
Address: Department of Mathematics and Statistics, P.O.Box 68,
00014 Univ. of Helsinki, Finland
E-mail: tpl@rni.helsinki.fi

Name: Dr Dean McLaughlin
Affiliation: Leicester
Address: Department of Physics & Astronomy, University of Leicester,
University Road, Leicester, LE1 1RH
E-mail: dean.mclaughlin@astro.le.ac.uk

Name: Dr John Magorrian
Affiliation: University of Oxford
Address: Theoretical Physics, 1 Keble Road, Oxford OX1 3NP
E-mail: j.magorrian1@physics.ox.ac.uk

Name: Dr Panos Patsis
Affiliation: Greek Academy of Sciences
Address: Research Center for Astronomy, Academy of Sciences, Soranou Efesiou
4, GR-11527, Greece
E-mail: ppatsis@cc.uoa.gr

Name: Prof Hans-Walter Rix
Affiliation: Max-Planck Society
Address: Max-Planck Institut fuer Astronomie, Konigstuhl 17,
Heidelberg, 69117, Germany
E-mail: rix@mpia.de

Name: Prof Annie C. Robin
Affiliation: Observatoire de Besançon
Address: BP1615 F-25010 Besançon cedex
E-mail: annie@obs-besancon.fr

Name: Dr Arnaud Siebert
Affiliation: AIP Potsdam
Address: An der Sternwachte 16, D-14482 Potsdam
E-mail: siebert@rave.as.arizona.edu

Name: Dr Martin C. Smith
Affiliation: Kapteyn Astronomical Institute
Address: P.O. Box 800, 9700 AV Groningen, The Netherlands
E-mail: msmith@astro.rug.nl

Name: Dr Mark Wilkinson
Affiliation: Institute of Astronomy, Cambridge
Address: Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
E-mail: markw@ast.cam.ac.uk

Name: Dr. HongSheng Zhao
Affiliation: Univ. of St Andrews
Address: School of Physics and Astronomy,
Univ. of St Andrews, KY16 9SS, Fife, UK

Statistics

The attendees were distributed in age as follows:
age 20-30: 8 age 31-40: 10 age 41-50: 8 age 51+: 2

The gender distribution was: F: 3 M: 25

Geographical distribution:

BE: 2	GR: 1
DE: 4	MX: 1
FI: 3	NL: 5
FR: 3	UK: 9