100 MILLION RADIAL VELOCITIES: HOW TO GET THEM

U. Bastian

Astronomisches Rechen-Institut, Mönchhofstrasse 12-14, D-69120 Heidelberg, Germany

ABSTRACT

The astrometric interferometer satellite GAIA, proposed for ESA's Horizon 2000+ programme, is supposed to provide 3-dimensional galactic locations (i.e., positions and parallaxes) and 2-dimensional velocities (i.e., proper motions) for about 50 million stars, mostly of magnitude 15 to 16. The third velocity component, which is also needed for full galactic kinematics and dynamics, cannot be derived from astrometric measurements.

I propose a large-scale observing campaign to measure 100 million precise radial velocities. At least two observations per star are needed to achieve some discrimination against binaries. 100 million measurements within a reasonable project time of a few years, this means roughly one measurement per second (even disregarding daylight, repair times etc.). I demonstrate that this is achievable using two dedicated medium-sized telescopes (one in each terrestrial hemisphere) with special multi-fiber-linked echelle spectrographs and CCD detectors.

There would be very big scientific spinoffs from such an observing campaign even long before the start of GAIA. Rotational velocities, metallicities and spectral types for 50 million stars would be determined as a mere side result of the radial-velocity project. Such a campaign could perhaps be executed as follow-up project on existing survey telescopes, e.g., at Apache Point Observatory after the completion of the Sloan Digital Sky Survey.

Key words: radial velocities; metallicities; rotational velocities; spectral classification; sky surveys; GAIA; Sloan Digital Sky Survey.

1. INTRODUCTION

The scientific need for radial velocities, spectral types and metallicities for the GAIA programme stars was explained by Favata & Perryman (1995) in the preceding paper (this volume). This need not be repeated. However, with existing instrumentation it is impossible to derive 100 million precise radial velocities for stars of typically magnitude 15 to 16 within the perhaps 20 years till the end of the GAIA mission.

Favata & Perryman gave a fairly detailed analysis of a slitless spectrograph configuration in a scanning observing mode, to be used either on ground or in space. They demonstrate that such a device could in principle yield the needed amount of data within a few years, and they advocate serious consideration of its implementation on board GAIA. The beauty of having the spectroscopy done on the same craft as the astrometry is obvious: a single instrument giving full 6-dimensional galactic structure and kinematics must have been the dream of any astronomer investigating the Galaxy. The stable environment in space gives very clean and very consistently calibrated data.

The disadvantages are equally obvious: the spectroscopic 'appendix' adds complexity to an already very complex device. The spectral and radial-velocity survey would become available only 20 years or so from now. There would be huge scientific spinoffs from such a survey, even without the accompanying astrometry. These could be harvested much earlier if the task were performed on the ground. And, of course, they would be independent of GAIA's success. Therefore the ground-based option should also be considered seriously, especially since the ground allows more flexibility in the choice of telescope size and instrument configuration.

2. MULTI-FIBER-FED SLIT SPECTROGRAPHS

In the following I sketch two multi-fibre-linked slit spectrograph configurations working in a pointed mode on ground. The aim of the present paper is not to elaborate the concepts in any detail, but just to point out their feasibility, and to give a stimulus and incentive to groups that might be able to work them out and implement them. For both configurations I shall assume two medium-sized (2.5 m) telescopes, one for each terrestrial hemisphere. They will be assumed to actually work during one third of the time, the rest being lost by daylight, maintenance, calibration and so on. A field of view of two square degrees can be safely assumed, since the field need not be perfectly aberration-free in fiber-linked spectroscopy. Positioning of the fiber entrance pupils within the field is supposed to be done by a robot capable of handling 1000 fibers. Such a very big robotic device is feasible nowadays; in fact one such is under construction for the AAT (according to Maddox, 1995). The astrometric information needed for the positioning of the fibers would be taken from direct images taken in a neighbouring off-axis field of view. These can be taken during each spectroscopic exposure, in preparation of the next one. Arcsec-level precision is sufficient.

The exit pupils of the fibers are arranged along the entrance slit of the spectrograph. Only one echelle order can thus be used, all others are removed by filters. All spectra are imaged side by side onto a very wide one-order CORAVEL mask (in the first configuration) or directly onto the CCD (in the second configuration).

3. CORAVEL-TYPE CONFIGURATION

The capacity of CORAVEL (for a description see Baranne et al., 1979), as well as all other existing correlation spectrometers, is limited to at most a few ten thousand measurements per year by the fact that it can treat only one object at a time and by the quantum efficiency of the photocathode used as light detector. This limitation can be overcome by the proposed multi-fiber-fed instrument recording onto a CCD. After passing the CORAVEL mask the spectra are re-combined into 'white' light by a prism. An image of the spectrograph entrance slit is then focused onto an elongated array of CCDs. The long direction of the array is along the line of fibre images. The short direction accomodates the individual CORAVEL transmission intensities for each spectrum. The stepping of the spectra across the CORAVEL mask is accompanied by charge shifts on the CCD. In this way the whole correlation functions (perhaps 100 intensity points per spectrum) are recorded before readout of the chips.

The performance of such a configuration can be estimated as follows.

According to Gerbaldi et al. (1989) CORAVEL reaches a precision of 1 km/s for a star of $B = 10.4$ mag with 15 s of integration time at the ESO 1.5 m telescope. Rescaling this exposure time to the conditions specified in Section 2 and the instrument described just now (bigger telescope, higher detector quantum efficiency, only one echelle order instead of 18, 1000 objects at a time, magnitude $B = 16$ instead of 10.4) results in an exposure time of slightly more than 2000 s for one set of correlation functions. For 100 million observations this translates into a 10.5 years operational phase with two telescopes observing one third of the time.

This time is uncomfortably long. Optimizing the instrument or increasing the size of the telescopes might decrease it. But the following section shows that a direct recording of the spectra and subsequent correlation with template spectra is more efficient.

4. DIGITAL CORRELATION CONFIGURATION

Favata & Perryman set the same goal of 1 km/s for a (slitless) configuration with direct recording of spectra onto a CCD (and subsequent numerical cross-correlation with digital templates in the computer). This goal corresponds to a signal-to-noise ratio of 5 (per pixel) in a typical echelle order of 40 Å and the typical echelle spectral resolution of 30000. With these requirements and an assumed 1-m telescope they reach a limiting magnitude of $V = 13.5$ mag with an exposure time of 9 minutes (see Section 8 of their paper). Doing a similar scaling calculation to the telescopes and conditions assumed in the present paper, and to a limiting magnitude of $V = 15.3$ mag (corresponding to $B = 16$ as in the preceding section), one finds an exposure time of about 450 s for one set of spectra. For 100 million observations this translates into a 2.1 years operational phase with two telescopes observing one third of the time. The parallel digital processing of (up to 1000) spectra recorded in the preceding exposure does not impose severe requirements on the computer. It needs about one million floating-point operations per second.

The difference to the CORAVEL-type configuration is mainly due to the simultaneous usage of all photons coming from the stars. The CORAVEL mask blocks a big part of them. Moreover, part of the photons catched by CORAVEL are unavoidably lost while the instrument is taking data points outside the correlation dip, i.e., at radial velocities far from the actual velocity of an individual star. Since, in addition, the CORAVEL-type configuration involves the more complex instrument, one can drop it in favour of the direct spectroscopy configuration.

The time of 2.1 years is not a precise number, of course. Surely the exposure times can be shortened by improving the instrument design. For instance, one could use longer echelle orders, or even a few instead of just one. On the other hand, the whole job can probably not be done in only two years, since the simple scaling calculation does not include considerations of sky observability, the setting times of telescopes and fibres (which may be quite significant since the individual exposure times are only of the order of 7.5 minutes), and a certain waste of time because one will not always be able to use all the 1000 fibres.

5. THE SLITLESS OPTION FROM THE SAME POINT OF VIEW

It is interesting to compare the scanning slitless spectrograph and the pointing slit spectrograph directly. Using the same telescope and spectrograph parameters, and the same performance goals, one arrives at the same exposure time (7.5 minutes) per spectrum. With a (realistic) 2000 pixels square CCD a quarter of a square degree can be observed with the slitless configuration at any time. This has to be scaled up to the whole sky of 41252 square degrees. With the same conditions as before (two telescopes etc.) this leads to an operational project phase of 3.5 years.

The main difference to the time needed for the slit configuration lies in the fact that on average only 300 stars (out of the 50 million) are present on the 0.25 square degree field. Thus this time may be drastically improved by using bigger CCDs. On the other hand, the above estimate does not include the noise due to the night sky, which in the slitless configuration contributes about as many photons as a 15–16 mag star.

6. SLITLESS OR SLIT SPECTROGRAPH?

Table 1 gives a brief summary of the basic advantages of one of the options over the other, and vice versa. It turns out that the primarily quantitative arguments (i.e. instrument complexity and photon efficiency, in other words: money) argue in favour of the slitless configuration, while the more qualititative arguments (zero-point problem, source confusion, observing flexibility and the like) tend to put preference on the slit spectrograph.

All the possible additions and modifications as discussed by Favata & Perryman, e.g. the simultaneous collection of low-dispersion classification spectra, are applicable to both configurations. Thus they need not be discussed here.

Table 1. Advantages and disadvantages of a scanning slitless spectrograph compared with a pointing slit spectrograph.

	Scanning slitless spectrograph		Pointing slit spectrograph
+	no moving parts, thus usable on GAIA		applicable on ground only
+	comparatively simple instrument		very complex due to the many fibers
+	working continuously (no dead time) and easy to operate automatically		dead time due to resetting telescopes and fibers
+	no problem for high-velocity stars		high-velocity stars pose problems
	high-precision astrometry (0.05 arcsec) needed as input	+	only arcsec-level astrometry needed
	bright stars pose a problem	+	no problem
	source confusion is large	+	no problem
	zero-point calibration is difficult	+	comparatively simple
	sky background is high at $V = 15 - 16$	+	no problem
	magnitude limit is very strict	+	flexibility due to free choice of exposure time for specific objects or regions
	the celestial poles pose a problem	+	no problem
	more photon-efficient with large CCDs		more photon-efficient with 2 kpix CCDs

7. DISCUSSION

The two options (slitless or slit spectrograph) discussed in the preceding section do not exclude each other. Quite on the contrary, the table shows that they might complement each other. The slitless option has special problems close to the celestial poles and in very crowded areas. On the other hand, the very big number of 1000 fibers for the slit spectrograph was assumed only because the instrument was supposed to cover the whole sky.

If an observing project using a multi-fiber-fed slit spectrograph would concentrate on the real problem areas of the slitless configuration, it could do very well with existing fiber robots of 100 to 200 fibers. Those areas cover just about 5–10 percent of the sky. Mounted to a much smaller telescope, with a correspondingly larger field of view, it could also treat the bright-star problem of the slitless option.

The present paper is mainly aimed at scientific groups that might be able to implement and execute an observing project of the kind proposed here. On one hand, there are existing survey telescopes, which could be supplied with a fiber robot and echelle spectrograph after having completed their present survey task. The 2.5 m telescope on Apache Point Observatory, built and presently being used for the Sloan Digital Sky Survey (Kent 1994, Kent et al. 1994), is an outstanding example.

On the other hand, the forthcoming 8 m and 10 m telescopes will probably lower the demand for observing time on the 2 m and even the 3 m to 4 m telescopes. Thus it might be possible to have more medium-sized telescopes available for survey work in the near future. One or two of them might be equipped to carry through a survey programme of the type proposed here.

It should be pointed out that such a survey is in no way tied to GAIA or any other astrometric project. In fact, a big and deep survey for stellar radial velocities, metallicities, rotational velocities and spectral classifications would in itself be a big step forward for research on galactic kinematics and stellar populations, as well as for many astrophysical topics. Such scientific spinoffs, more closely discussed by Favata & Perryman in this volume, could be harvested by a ground-based programme even long before the launch of GAIA.

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REFERENCES

Baranne, A., et al., 1979, *Vistas in Astronomy*, 23, 279

Favata, F., Perryman, M.A.C., 1995, ESA SP–379, this volume

Gerbaldi, M., et al., 1989, *The ESO Messenger*, 56, 12

Kent, S.M., 1994, *Astrophys. Space Sci.*, 217, 27

Kent, S.M., et al., 1994, *Astron. Soc. Pacific Conference Series*, Vol. 61, 205

Maddox, J., 1995, *Nature*, 374, 591