PARALLEL ACQUISITION OF RADIAL VELOCITIES AND METALLICITIES FOR THE GAIA MISSION

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ABSTRACT

We discuss possible options for the acquisition of radial velocities in parallel with the astrometric data for the global astrometry mission GAIA, currently under study in the framework of the scientific programme of the European Space Agency. The scientific rationale of a parallel radial velocity programme, in the light of the recent evolution of the GAIA concept toward significantly fainter magnitudes, is discussed, and a possible instrument concept is presented. The approach currently being investigated could yield radial velocities accurate to $\simeq 10\,\mathrm{km\,s^{-1}}$ for targets as faint as $V \simeq 17$ mag, and as accurate as $\simeq 1\,\mathrm{km\,s^{-1}}$ for relatively bright stars ($V \simeq 10$–12 mag). These performance figures, derived for a realistic instrumental configuration, compatible with the GAIA configuration currently being studied, would greatly enhance the scientific return from GAIA itself, and produce significant science of its own.

Key words: radial velocities; space astrometry; GAIA; spectral classification; abundances.

1. INTRODUCTION

The scientific goal of GAIA, one of the missions currently being considered for implementation in the framework of the long-term scientific programme (Horizon 2000+) of the European Space Agency, is to perform an astrometric all-sky survey, in the same spirit of Hipparcos, but to a limiting precision two orders of magnitude better. The limiting magnitude will be much fainter than Hipparcos, giving access to a large fraction of the visible Galaxy. Conventional astrometric measurements will however provide only five of the six phase-space coordinates for its targets (i.e. the three-dimensional position and the two components of the transverse velocity). The sixth component (the radial velocity) is necessary to have a complete picture of the dynamics, as well as of other properties, of the target sample. Radial velocities can be measured through spectroscopic observations, and the inclusion of a separate, dedicated spectroscopic payload to the GAIA mission (which would measure, in addition to the radial velocities, stellar effective temperatures, spectral types and abundances) is currently being considered. In the present paper we will present the scientific rationale for the inclusion of a radial velocity payload to GAIA, sketch the scientific requirements which drive it and describe some possible options for the instrument design.

The importance of the acquisition of radial velocities (as well as of other 'auxiliary' scientific data) for the astrometric targets in the framework of the GAIA mission was first discussed by Perryman (1994), and the idea of a radial velocity payload to be added to the main GAIA interferometric package was already discussed in detail by Favata & Perryman (1995). However, at the time the GAIA concept envisaged a less performing interferometric package, limited, by the use of a modulating grid on the focal plane, to a magnitude of about 16, and operating in a band more or less centered on the classical V band. With the developments in the field of CCD detectors and a large optical design effort, the GAIA concept has evolved significantly, and the configurations currently being studied foresee direct detection of the interferometric fringes, which should enable the detection of much fainter stars (likely down to $V \simeq 20$ mag) albeit at a reduced accuracy with respect to that achievable for the brighter stars (of the order of $\simeq 1\,$mas at $V \simeq 20$ mag, rather than the $\simeq 10\,\mu$as expected at $V \simeq 15$ mag). The concept being studied for the acquisition of parallel radial velocities (and other auxiliary data) has therefore correspondingly evolved, to match the shift toward fainter magnitudes of the interferometric package.

The push toward fainter (and perhaps) redder targets (with the original accuracy figures for brighter stars still standing), has led to a substantial augmentation of the science case for GAIA. While none of the original science goals has been dropped, the addition of a large number of faint, lower accuracy targets for which essentially only accurate proper motions will be measured (most of them being too far away for useful parallaxes to be derived at the reduced astrometric precision available for the fainter targets) has turned GAIA into a very powerful tool for studying the dynamical evolution of the Galaxy through its faint and red kinematic tracers, supplementing its original scientific goals in fields such as stellar physics, dynamics of stellar systems, the search for planets around nearby stars or the study of relativistic effects.

The scientific goals of the proposed radial velocity acquisition programme have correspondingly been revised to include the new scientific requirements coming from the inclusion of fainter targets: radial velocities will be paramount in using the fainter GAIA targets as kinematic tracers of the Galactic potential. The radial velocity acquisition system has therefore been re-thought to push toward fainter magnitudes. As shown in Section 3 the 'best' possible performance that can be envisaged from an instrument of size compatible with the GAIA spacecraft envelope, on the basis of the photon statistics, is some $\simeq 10\,\mathrm{km\,s^{-1}}$ at magnitudes $V \simeq 17$ mag, or possibly even fainter, depending on the details of the detector technology.

2. SCIENTIFIC RATIONALE

The scientific case for parallel acquisition of radial velocities on board GAIA was already discussed in some detail in Favata & Perryman (1995). In the following we will briefly review the case presented there including changes brought by the push toward fainter and redder objects.

The motivations leading to the inclusion of a separate radial-velocity instrument on board GAIA include (in addition to the population studies to be performed for the fainter targets and discussed in detail below) the search for binaries and the removal of the effect of perspective acceleration on the astrometric measurements for the higher motion nearby stars. In addition to being *per se* a scientifically valuable project, the identification of binaries in the observed sample would allow to keep track of the binary status of the source in the reduction of the astrometric data, as discussed by Wielen (1995). The determination of source metallicity, at a higher level of accuracy than possible photometrically (and possibly for a limited number of individual elements) would allow detailed study of the chemical evolution of the different components of the Galaxy, and is a natural 'side-product' of radial velocity determination.

The maximum useful accuracy on time-average radial velocity measurement for statistical studies is determined by some intrinsic 'cosmic' factors (i.e. intrinsic to the source). Studying individual sources at a higher level of precision is obviously useful, while for statistical studies higher accuracies are not likely to be necessary. The two most relevant effects in the present context are the influence of undetected long-period binaries in the sample and the presence of large-scale atmospheric motions in the cool giants which are likely to constitute one of the dominant contributor to the populations detected at faint magnitudes (as well as one of the more useful kinematic tracers). Both requirements yield approximately the same number on the limit to the radial velocity precision for time-averaged measurements, i.e. $\simeq 1\,\mathrm{km\,s^{-1}}$.

The main usage of the radial velocity acquired at the fainter end will however not be in terms of velocities of individual objects, but rather in terms of separating the different Galactic (sub)populations and studying the distributions of their velocities. The current knowledge on the velocity distributions of various populations can therefore be used to estimate the required velocity resolution (again at the faint end) and its compatibility with the foreseen instrumental limits.

As shown, for example, by Gilmore & Høg (1995), the stellar populations of the Galaxy can be divided, based on their velocity dispersion, in three groups, which can be called for convenience 'cold', 'warm', and 'hot'. The cold populations are the ones with low velocity dispersion, i.e. in general the young populations, such as the ones located in the spiral arms, or open clusters, or older but dynamically tightly bound populations such as those in globular clusters. Their velocity dispersion is in general lower than $10\,\mathrm{km\,s^{-1}}$, and therefore any plausible GAIA-based radial velocity programme will not be able to resolve their velocity distribution at the faint end. However, the foreseen instrument might be able to substantially resolve them at somewhat brighter magnitudes (i.e. $\simeq$ 13–15), where the large signal-to-noise ratio could provide velocity accuracies down to $\simeq 1\,\mathrm{km\,s^{-1}}$, providing useful data, for example for the brighter blue supergiants located in the spiral arms, or for the solar-type stars in most open clusters closer than $\simeq 1\,\mathrm{kpc}$.

The warm stellar populations include most of the Galactic disk (except for its youngest component), and the thick disk. They will be the dominant population detected by GAIA across much of the magnitude range, and have an intrinsic velocity dispersion of some $\simeq$ 20–30 $\mathrm{km\,s^{-1}}$, so that the $10\,\mathrm{km\,s^{-1}}$ which could be achieved at the fainter magnitudes would start to resolve their velocity distribution.

The hot population includes the Galactic bulge and halo, where the intrinsic velocity dispersion is much higher, i.e. of order $\simeq$ 80–100 $\mathrm{km\,s^{-1}}$. While a $10\,\mathrm{km\,s^{-1}}$ target precision would therefore allow detailed study of their kinematic behavior, their being intrinsic metal-poor will make velocity measurements on the Doppler shift in their spectra more difficult. Consequently a lower velocity accuracy (perhaps by a factor of two or so) may possibly be achievable for them.

2.1. Metallicity

High-resolution spectra would allow detailed determinations of the stellar photospheric metallicity to be performed. However, the lower-resolution spectra obtained by the GAIA radial velocity instrument as currently envisaged would still be useful for determining global metallicities (at a plausible precision of some 0.2 dex), at least in cool stars. Neural-network based classification techniques have been shown to be very efficient in determining both the effective temperature and the metallicity of low-resolution spectra (Bailer-Jones et al. 1997), and could likely be applied to derive a metallicity measurement for each target in an automated fashion.

The possibility of using spectra at these resolutions for determining the abundance of individual elements, and thus determining abundance ratios, which would allow a large scientific return in terms of studying the chemical evolution of the different Galactic populations, will need to be studied in detail.

3. A PRELIMINARY INSTRUMENT DESIGN

A radial velocity acquisition system (currently referred to as ‘ARVI’, for ‘Absolute Radial Velocities Instrument’) will be studied at rather detailed level as a potential part of the GAIA payload in the framework of the forthcoming Payload and Technology Study which will be performed by industry in the course of the next year (1998). Although the final configuration is likely to evolve in its details in the course of the study (whose purpose is also to verify that such a payload can be integrated in the GAIA system without disturbing the very demanding interferometric package), the general features of the instruments are unlikely to change dramatically.

The current scientific requirements of GAIA show (Section 2) that very useful science can be obtained already for accuracies in radial velocity, at the fainter end, of only $\simeq 10\,\mathrm{km\,s^{-1}}$. At low signal-to-noise ratios (i.e. $\simeq$ 5), given a sufficient observed spectral range, radial velocities can be well determined, for slowly rotating cool stars, within one or two tenths of a pixel, so that (assuming a central wavelength close to 5000 Å) the $\simeq 10\,\mathrm{km\,s^{-1}}$ translates into a resolving power of $\simeq$ 5000 per pixel. At high signal-to-noise ratios (i.e. for the brighter stars) the velocity resolution can be (assuming a sufficiently stable and well-calibrated instrument) as good as one hundredth of a pixel, implying a $\simeq 1\,\mathrm{km\,s^{-1}}$ resolution for the brighter stars.

The current preliminary design is centered around a $\simeq$ 90 cm diameter primary mirror (a size for which accommodation on board the GAIA spacecraft can be foreseen) and a spectral dispersion of $\simeq 1\,\mathrm{Å\,pix^{-1}}$, corresponding to some $50\,\mathrm{Å\,mm^{-1}}$ in a plausible optical configuration. This rather low spectral dispersion can be achieved without the need for an echelle system (as originally envisaged), but rather with a relatively simple grism system. The usage of a grism system (as opposed to an echelle system) has the advantage of a much higher efficiency, due both to the higher intrinsic efficiency of the grism (when compared with an echelle grating) and to the lower number of optical elements needed in the system. For the current assessment of the performance of the instrument we have assumed a total system efficiency of $\simeq$ 15 per cent.

The optical design of such a telescope should feature a large well-corrected field of view, to allow a maximum multiplexing advantage. One such design which has been already studied for space applications is the two-mirror, triply-reflecting design. The study made for the STARS asteroseismologic mission (Favata et al. 1996) used, for example, a 1 m diameter triply-reflecting telescope, with a well-corrected planar field of view in excess of 1.5 degree diameter (although with some vignetting at the edge). This could be housed, due to the folded optical path, in a compact package which would be compatible with its accommodation within the GAIA spacecraft. Other possible designs include Ritchey-Chretien telescopes with a field corrector.

The performance of this preliminary design for the ARVI instrument is shown in Figure 1, which shows the attained signal-to-noise ratio as a function of apparent V magnitude. The left-hand panel shows the signal-to-noise ratio obtained in a single scanning pass (assuming the nominal GAIA $120\,\mathrm{arcsec\,s^{-1}}$ scanning velocity), while the right-hand panel shows the signal-to-noise ratio obtained after summing together all the spectra acquired during individual scans. In both panels the horizontal dashed line marks the approximate minimum usable signal-to-noise ratio (i.e. 5) at which the spectra allow a velocity accuracy of $\simeq 10\,\mathrm{km\,s^{-1}}$. The continuous line is the final accuracy, the short-dashed line is the accuracy which would be obtained with a detector without read-out noise and the long-dashed line is the accuracy without detector noise or sky background.

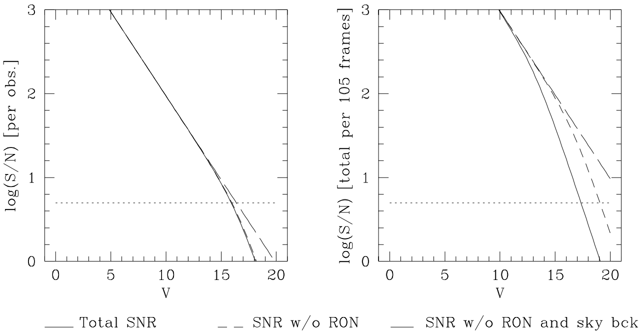

Figure 1. The performance of a 0.90 m diameter telescope for the acquisition of radial velocities, calculated using the sky scanning parameters currently assumed for the GAIA mission. The panels show the achievable signal-to-noise ratios as a function of apparent magnitude, for each individual great-circle scan (left panel) and for the sum of all the scans over a 5 yr lifetime (right panel). The dashed horizontal line shows the minimum useful signal-to-noise, fixed here at a value of 5. The continuous curve is the final accuracy taking into account the detector read-out noise (fixed here at 2 e^-) and the effect of the sky background in orbit. The short-dashed curve shows the performance of an ideal detector without read-out noise, while the long-dashed curve shows the performance of a hypothetical case with no sky background. Note how even a rather low read-out noise of 2 e^- affects the faint limit by almost two magnitudes. The detector assumed is an 8k×4k pixel CCD (mosaic) covering 2×1 degrees of sky.

The preliminary ARVI has a performance close to the one needed to explore the kinematic dispersion of much of the Galactic populations. Systemic radial velocities down to $10\,\mathrm{km\,s^{-1}}$ can be obtained, in the lifetime of the mission, down to $V \simeq 17$ mag, and some effort in the reduction of the CCD read-out noise could allow the limiting magnitude to be fainter. The data of Figure 1 have been evaluated assuming a read-out noise of $2\,e^-$, a figure considered achievable with present-day technology. Investment toward lower read-out noise detectors would, in the context of the ARVI development, be desirable, as it would have a large payoff in terms of number of accessible targets. Possible techniques can involve the slower reading of ‘useful’ pixels (using multiple read-out, the so-called ‘skipper’ technique) or going to photon-counting detectors (which have no intrinsic read-out noise).

3.1. An Input Catalogue?

It is worth noting that the final accuracy of $10\,\mathrm{km\,s^{-1}}$ for the faint stars ($V \simeq 17$ mag or fainter) is a 'systemic' radial velocity, obtained by averaging over a large number ($\simeq 100$) of individual spectra of very low signal-to-noise ratio. Each individual spectrum, would, for the fainter stars, have a signal-to-noise ratio as low as $\simeq 1$ per pixel, a value too low to allow any reliable scheme for on-board detection of spectra. Thus, the final ARVI data reduction scheme will at some stage along the chain need to have *a priori* knowledge of the position of its targets. This can be obtained either through the usage of a pre-defined input catalogue, or by making use of some detection scheme possibly linked to the photometric CCDs of the main GAIA interferometric package, where the undispersed, broad-band images of the same targets would yield a much higher signal-to-noise ratio, perhaps allowing reliable on-board detection.

A possible shortcoming of the input catalogue approach is that it may miss some interesting classes of objects which would in principle be observable but which may not be included in the input catalogue (for example because they would not be viable astrometric targets), but which would yield interesting science. These could include, for example, non point-like emission line objects (such as planetary nebulae, H II regions, compact SNR, etc.) whose integrated broad-band magnitude would be very faint, but whose individual emission lines will likely be bright enough to actually be easily detected in the spectrum. Also, galaxies with a high surface-brightness core may fall in this category. Obviously these categories of sources would be interesting targets for GAIA, if at all observable, but it is possible that the 'observable sets' of the interferometric and radial velocity instruments will not show complete overlap. If at all possible in light of the available telemetry budget, telemetering the data from the whole focal plane of the spectroscopic instrument should be seriously considered, as it would completely bypass these issues. It is worth noting that the foreseen data flow at the focal plane for the ARVI instrument ($< 1\,\mathrm{Mbit\,s^{-1}}$) is a very small fraction of the data flow produced by the interferometric detectors (expected to be of order several $\mathrm{Gbit\,s^{-1}}$).

3.2. The Choice of the Spectral Range

The usage of a lower spectral resolution makes the choice of the spectral region to be investigated less critical, as a much larger spectral region can be covered before being limited, for example, by confusion. A spectral coverage of a few hundred Å is feasible, which could include a Balmer line, allowing (lower precision) radial velocities to be derived also for early type stars.

Current suggestions for the spectral coverage include from the Hβ line at 4861 Å up to $\simeq$ 5400 Å, to include the Mg II complex, which would be useful as a luminosity class indicator in cool stars. This range also includes some of the forbidden oxygen transitions which could perhaps allow some non-stellar objects such as H II regions to be usefully observed.

4. OPEN ISSUES

Several issues will need to be studied in detail to go toward a mature instrument concept for parallel radial velocity acquisition on board the GAIA mission. Here we list some of the more important open points which will deserve further study:

Choice of the spectral resolution. The maximum velocity resolution achievable for a variety of stars, in particular for hot and cool giants, as well as for metal-poor stars, needs to be assessed with the help of detailed simulations.

Spectral range covered. Again, simulations of a wide variety of objects will be needed, investigating, in addition to the velocity-resolution issue, the capability of extracting luminosity-class information as well as (individual and global) metallicity.

Requirements on the attitude control. Given the large sky coverage on a single chip the requirements on both the uniformity in scanning velocity and in the transverse attitude accuracy are likely to be demanding. While this can in principle be solved by feeding real-time attitude information from the spacecraft to the radial velocity instrument, the various consequences need to be investigated in detail.

Impact on the interferometric mission. The main purpose of the GAIA mission remains the accurate interferometric astrometry. Given the very stringent requirements which are being derived, for example, on the stability of the payload, it will be necessary to assess in detail what the impact of an additional payload is on the interferometric package, on the principle that the interferometer requirements have precedence and must not be compromised.

Determination of the zero point. A slit-less spectrograph lacks an obvious way of inserting a reference wavelength in the focal plane. Various possible solutions have been suggested, including the usage of a gas cell with narrow absorption lines, or the usage of the astrometric information to reconstruct, *a posteriori*, the Doppler shift of the spectrum. A suitable solution will have to be investigated in detail in the light of the final ARVI design.

5. CONCLUSIONS

The case for the parallel radial velocity acquisition of spectroscopic information on board the GAIA satellite is, from the scientific point of view, compelling. The extension of GAIA toward fainter limiting magnitudes does not alter this fact, although it pushes the radial velocity concept toward a lower-resolution than initially envisaged.

A limited size instrument ($\simeq 0.9\,\mathrm{m}$) is likely to provide sufficient performance for sampling the radial velocity distribution of most of the Galactic populations which will be studied by GAIA. Although many detailed trade-offs remain to be done, such an instrument is likely to provide a strong enhancement of the scientific return of the GAIA mission, and its inclusion in the GAIA payload will be studied in the context of the forthcoming Payload and Technology Study for GAIA.

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