# Spectroscopic survey of the Galaxy with Gaia I. Design and performance of the Radial Velocity Spectrometer

- D. Katz<sup>1\*</sup>, U. Munari<sup>2</sup>, M. Cropper<sup>3</sup>, T. Zwitter<sup>4</sup>, F. Thévenin<sup>5</sup>, M. David<sup>6</sup>,
- Y. Viala<sup>1</sup>, F. Crifo<sup>1</sup>, A. Gomboc<sup>7,4</sup>, F. Royer<sup>8,1</sup>, F. Arenou<sup>1</sup>, P. Marrese<sup>2</sup>,
- R. Sordo<sup>2</sup>, M. Wilkinson<sup>9</sup>, A. Vallenari<sup>10</sup>, C. Turon<sup>1</sup>, A. Helmi<sup>11</sup>, G. Bono<sup>12</sup>
- M. Perryman<sup>13</sup>, A. Gómez<sup>1</sup>, L. Tomasella<sup>2</sup>, F. Boschi<sup>2</sup>, D. Morin<sup>1</sup>, M. Haywood<sup>1</sup>,
- C. Soubiran<sup>14</sup>, F. Castelli<sup>15,16</sup>, A. Bijaoui<sup>5</sup>, G. Bertelli<sup>10</sup>, A. Prsa<sup>4</sup>, S. Mignot<sup>1</sup>,
- A. Sellier<sup>1</sup>, M.-O. Baylac<sup>1</sup>, Y. Lebreton<sup>1</sup>, U. Jauregi<sup>4</sup>, A. Siviero<sup>2</sup>, R. Bingham<sup>17,3</sup>,
- F. Chemla<sup>1</sup>, J. Coker<sup>3</sup>, T. Dibbens<sup>3</sup>, B. Hancock<sup>3</sup>, A. Holland<sup>18</sup>, D. Horville<sup>1</sup>,
- J.-M. Huet<sup>1</sup>, P. Laporte<sup>1</sup>, T. Melse<sup>1</sup>, F. Sayède<sup>1</sup>, T.-J. Stevenson<sup>18</sup>, P. Vola<sup>1</sup>, D. Walton<sup>3</sup> and B. Winter<sup>3</sup>.
- <sup>1</sup> Observatoire de Paris, GEPI, 5 Place Jules Janssen, F-92195 Meudon France
- <sup>2</sup>Osservatorio Astronomico di Padova INAF, sede di Asiago, 36012 Asiago (VI), Italy
- <sup>3</sup> Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK
- <sup>4</sup> University of Ljubljana, Dept. of Physics, Jadranska 19, 1000 Ljubljana, Slovenia
- <sup>5</sup>O.C.A., BP 4229, F-06304 Nice Cedex 4, France
- $^6$  University of Antwerp, Middelheimlaan 1, B-2020 Antwerpen, Belgium
- <sup>7</sup> Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead, CH41 1LD, UK
- <sup>8</sup>Observatoire de Genève, 51 chemin des Maillettes, CH-1290 Sauverny
- <sup>9</sup>Institute of Astronomy, Madingley Road, cambridge CB3 0HA, UK
- <sup>10</sup> INAF Osservatorio Astronomico di Padova, Vicolo Osservatorio 5, 35122 Padova, Italy
- <sup>11</sup>Kapteyn Astronomical Institute, P.O.Box 800, 9700 AV Groningen, Netherlands
- <sup>12</sup> INAF Rome Astronomical Observatory, Via Frascati 33, 00040 Monte Porzio Catone, Italy
- <sup>13</sup> Research and Scientific Support Department of ESA, ESTEC, Postbus 299, Keplerlaan 1, Noordwijk NL-2200 AG, the Netherlands
- <sup>14</sup>Observatoire Aquitain des Sciences de l'Univers, UMR 5804, 2 rue de l'Observatoire, 33270 Floirac, France
- <sup>15</sup>CNR-Istituto di Astrofisica Spaziale e Fisica Cosmica, Via del Fosso del Cavaliere, 00133, Roma, Italy
- <sup>16</sup>INAF-Osservatorio Astronomico di Trieste, via G.B. Tiepolo 11, 34131 Trieste, Italy
- <sup>17</sup>Optical Design Service, Cambridge, 29 Millington Road, Cambridge CB3 9HW, UK
- <sup>18</sup> University of Leicester, Space Research Centre, University Road, Leicester, UK

Accepted . Received ; in original form

# ABSTRACT

The definition and optimisation studies for the Gaia satellite spectrograph, the Radial Velocity Spectrometer (RVS), converged in late 2002 with the adoption of the instrument baseline. This paper reviews the characteristics of the selected configuration and presents its expected performance. The RVS is a  $2.0 \times 1.6$  degree integral field spectrograph, dispersing the light of all sources entering its field of view with a resolving power  $R = \lambda/\Delta\lambda = 11500$  over the wavelength range [848, 874] nm. The RVS will continuously and repeatedly scan the sky during the 5 years of the Gaia mission. On average, each source will be observed 102 times over this period. The RVS will collect the spectra of about 100-150 million stars up to magnitude  $V \simeq 17-18$ . At the end of the mission, the RVS will provide radial velocities with precisions of  $\sim 2$  km s<sup>-1</sup> at V = 15 and  $\sim 15 - 20$  km s<sup>-1</sup> at V = 17, for a solar metallicity G5 dwarf. The RVS will also provide rotational velocities, with precisions (at the end of the mission) for late type stars of  $\sigma_{v \sin i} \simeq 5 \text{ km s}^{-1}$  at  $V \simeq 15$  as well as atmospheric parameters up to  $V \simeq 14-15$ . The individual abundances of elements such as Silicon and Magnesium, vital for the understanding of Galactic evolution, will be obtained up to  $V \simeq 12-13$ . Finally, the presence of the 862.0 nm Diffuse Interstellar Band (DIB) in the RVS wavelength range will make it possible to derive the three dimensional structure of the interstellar reddening

#### 1 INTRODUCTION

Understanding the Milky Way and its neighbourhood, both as a template of the formation and evolution of galaxies and as a laboratory of stellar physics, is one of the great astrophysics challenges at the beginning of the 21st century. The *Gaia* satellite (Perryman et al. 2001) was conceived and designed to constitute a major leap forward in this field. *Gaia* was selected as a Cornerstone of the European Space Agency (ESA) Horizon 2000+ programme in October 2000 and confirmed as part of the ESA Cosmic Vision programme in May 2002 and again in November 2003. The satellite launch is scheduled to take place "no later than 2012" and all the current scientific and industrial studies are consistent with a launch date in mid-2010.

Gaia's payload consists of 3 instruments: an astrometric instrument, a multi-band photometer (observing in 5 broad and 11 medium-band filters) and a spectrometer which will continuously and repeatedly scan the sky during the 5 years of the mission. On average, 102 spectra will be obtained per source. The astro-photometric "sample" will be complete up to the Gaia magnitude G=20 ( $G-V \simeq -0.36$  for a solar metallicity G5V star) and will contain more than a billion stars from the Galaxy and the Local Group. The huge size of the sample (about 1% of the entire stellar content of the Milky Way galaxy) and the accuracy and wealth of information collected about the spatial, kinematic and chemical distributions of the stars will allow Gaia to decipher many aspects of the origin and evolution of our Galaxy. Moreover, given the very large number of stars surveyed, even the briefest stages of stellar evolution have a very high probability of being observed by Gaia. Gaia will also detect and characterise several thousand extra-solar planetary systems. It will observe some  $10^5$  to  $10^6$  minor bodies in the solar system, thousands of galaxies, some  $5 \times 10^5$  quasars, about  $10^5$ extragalactic supernovae and will provide an accurate determination of several fundamental physical and cosmological parameters (e.g.  $\gamma$ ,  $\dot{G}/G$ ,  $\Omega_M$  or  $\Omega_{\Lambda}$ ).

The initial concept of Gaia was developed around the astrometric instrument. However, based on the experience of *Hipparcos* (Gerbaldi et al. 1989; Mayor et al. 1989; Binney et al. 1997), it was clear that the capability of making radial velocity measurements would be central to the successful attainment of the main Gaia science goals. By supplying the third component of the velocity vector (the other two being provided by the tangential motions), the velocity along the line of sight is crucial for the our understanding of the kinematics and dynamics of the Galaxy. Radial velocities are also necessary to correct the astrometric data for perspective acceleration (an apparent displacement on the sky induced by line-of-sight motion and which varies quadratically with time): simulations predict that the proper motions and positions of  $\simeq 10^5$  stars (unknown a priori) would be significantly biased if this effect was not removed. Finally, multi-epoch radial velocities are extremely valuable for the detection and characterisation of multiple systems and stellar variability. As Gaia was taking shape, several studies were investigating the feasibility, merits and drawbacks of the acquisition of radial velocities from the ground and from space (Perryman 1995; Favata & Perryman 1995). In 1997, the decision was made to include a spectrograph on board Gaia.

A first concept of the spectrograph was designed in 1998 by Matra Marconi Space (now Astrium-SAS, Toulouse). Following the approval of Gaia, ESA established, in June 2001, sixteen scientific working groups to support the development of the satellite and to prepare for the scientific analysis of the data. One of those groups was charged with the optimisation of the spectrograph, named the "Radial Velocity Spectrometer" (RVS), with respect to the *Gaia* science case. During the following 18 months, the RVS Working Group, with the support of Astrium, reviewed and refined the scientific objectives and priorities for the spectrograph, assessed its performance and compared the advantages and disadvantages of several potential RVS configurations. The scientific requirements and the technical constraints converged toward a refined scientific case and a new spectrograph concept in November 2002. The main modification with respect to the Matra Marconi design is the increase of the resolving power. A broader scientific case has also been associated with the revised configuration of the spectrograph. The acquisition of sufficiently accurate radial velocities for the largest possible sample of stars remains the key scientific objective of the RVS. Radial velocities are fundamental for the proper understanding of the Milky Way structure, origin and history. However, the increased resolution will make it possible, without affecting the radial velocity performance, to address a wide variety of issues in stellar physics: binarity, evolution, rotation, pulsation and variability, atmospheric chemistry, mixing processes and abundance peculiarities.

The RVS science case and general characteristics (e.g. spectral resolution, wavelength range) have now been defined. The more detailed design features (such as the number and type of CCDs) remain to be confirmed. This paper presents the revised and optimised baseline of the Radial Velocity Spectrometer: instrument concept (§ 2.1), optical (§ 2.2) and focal plane (2.3) characteristics. Although the instrument concept is expected to evolve in future phases, it should remain broadly within the parameters described here. This paper also presents the RVS calibration (§ 2.4) and observational (§ 2.5) strategies. Finally, it reviews the stellar and interstellar parameters that will be provided by the RVS spectra, namely, radial (§ 3.2) and rotational (§ 3.4) velocities, atmospheric parameters and individual abundances (§ 3.3) as well as interstellar reddening (§ 3.5).

The *Gaia* spectroscopic survey is expected to lead to major improvements in our understanding of the kinematical, dynamical and chemical structure and history of the Milky Way, as well as in our comprehension of stellar physics and evolution. Moreover, it will be ideally suited to the identification and characterisation of multiple systems. The expected scientific harvest is discussed in a companion paper (Wilkinson et al. 2004).

# 2 RVS DESIGN

#### 2.1 Instrument concept

The Radial Velocity Spectrometer is an integral field spectrograph: it uses neither slits, nor fibres, but disperses all of the light entering its  $2.00^{\circ} \times 1.61^{\circ}$  field of view. As with the other *Gaia* instruments, it will continuously and repeatedly scan the sky, observing each object, on average, at 102 successive epochs (see § 2.5).

The choice of the spectrograph wavelength range ([848, 874 nm: Munari 1999) was motivated by a number of considerations. It is close to the peaks of the energy distributions of the RVS principal targets: G and K type stars. In F, G and K stars, there are three strong core-saturated ionised Calcium lines in this range, which allows the measurement of radial velocities even at very low signal to noise ratios (i.e.  $\sigma Vr \simeq 15 \text{ km s}^{-1} \text{ at } S/N \simeq 1 \text{ per pixel, for a K1V}$ type star - see § 3.2) as well as in very metal poor stars. In early type stars, this spectral region is dominated by lines of the Hydrogen Paschen series, which are visible even in very rapidly rotating stars. It contains a Diffuse Interstellar Band (DIB), located at 862.0 nm, which appears to be a reliable tracer of the interstellar reddening (§ 3.5): this will be used, together with the photometric data, to derive a three-dimensional map of Galactic interstellar extinction. In addition, the extinction in the RVS domain will roughly be a factor of two smaller than in the V band. This will allow the probing of the Galactic disk over greater distances than would be feasible at 550 nm. Finally, this spectral range is almost free of telluric absorption features and is therefore usable from the ground for pre-launch preparatory (and possible complementary, post-mission) observations (§ 3.1).

In its original conception, the spectrograph had an effective resolving power  $R = \lambda/\Delta\lambda = 5750$ . During the 18 months of the optimisation phase (June 2001 - November 2002) the RVS working group compared the merits and drawbacks of a broad range of resolutions from R = 5000to 20000. The obvious advantage of the "high" resolutions is that they carry more spectral information than the "low" ones. The "weak" lines are sharper, the contrast between lines and continuum is better and the rate of line blending is lower. Therefore, the high resolution spectra provide more accurate diagnostics for the determination of stellar parameters (e.g. radial and rotational velocities, atmospheric parameters - see § 3) of most stars except the "faintest". Moreover, for  $R \geq 10000$ , numerous lines contained in the RVS infra-red wavelength range are unblended and it becomes possible to determine the individual abundances of several chemical species and in particular of alpha elements (e.g. Magnesium, Silicon - see § 3.3). However, the "high" resolutions also present a drawback. The RVS is an integral field spectrograph. As a consequence, in regions of high stellar density, the spectra of neighbouring sources will overlap and the mean rate of overlap grows linearly with resolution. Numerical simulations have shown that it will be possible, to a certain extent, to deconvolve the stacked spectra (Zwitter 2003) – see § 3.2. Even so, in very crowded areas the faintest sources will be lost in the noise. In those very dense regions, the limiting magnitude that the RVS can reach is a decreasing function of the resolution.

After extensive consideration within the working group of the advantages and disadvantages of resolving powers between R=5000 and 20000, a resolving power R=11500 was shown to be optimal for the fulfilment of Gaia's scientific

Table 1. Summary of the RVS general characteristics.

Spectrograph type	Integral field
Observing mode	Scan mode
Field of view size	$2.00^{\circ} \times 1.61^{\circ}$
Wavelength range	[848, 874] nm
Resolving power $(R = \lambda/\Delta\lambda)$	11500
Dispersion orientation	along scan
Integration time (per transit)	99 s

objectives. This resolution will allow the radial velocities of late-type stars to be determined with a precision  $\sigma V_r \leq 10$ -20 km s<sup>-1</sup> up to  $V \simeq 17$ -18 (reaching a precision of the order of 1 km s<sup>-1</sup> or better for the brightest targets), over about 90% of the sky (Sect 3.2). The rate of spectral overlap will be lower at R=11500 than at higher resolution, thereby allowing the RVS to probe fields of higher stellar density. Moreover, with the resolution R=11500 it will be possible to study the chemical pattern of the sources up to  $V \simeq 12$ -13 (Sect 3.3), while a lower resolution R=5750 did not allow the derivation of individual abundances because of too much line blending and insufficient contrast between lines and continuum. Table 1 summarises the global characteristics of the Radial Velocity Spectrometer.

#### 2.2 Optics

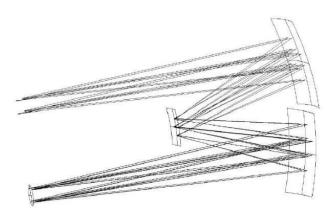
Gaia will scan the sky with three telescopes. Two of them illuminate the astrometric focal plane (which also contains the broad-band photometric detectors). The third one, the Spectro telescope, is shared by the Radial Velocity Spectrometer and the medium-band photometer. The viewing directions of the three telescopes are located in the same plane.

The Spectro telescope which illuminates both the RVS and the medium-band photometer is made of three Silicon-Carbide (Si-C), off-axis, rectangular mirrors. It has an entrance pupil of 0.25 square metres and a focal length of 2.1 m. The 11 medium-bands of the photometer cover a wavelength range from the near UV ( $\simeq 300$  nm) to the near infrared ( $\simeq 1000$  nm). The mirrors are coated with Aluminium which, unlike other metals, exhibits a reflectivity greater than 85% over the whole photometer wavelength range<sup>2</sup>.

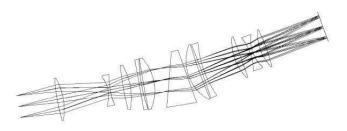
Two optical configurations remain under consideration for the RVS. The first, proposed by R. Bingham, is based on the Offner Relay concept (see Reininger (1994) for earlier work on this concept). It is made of three mirrors: two concave (the primary and tertiary mirrors) and one convex (the secondary mirror). The wavelengths are dispersed by a grating ruled on the secondary mirror. The second optical configuration being considered follows a classical arrangement of (i) a dioptric collimator, which parallelises the light rays coming from the same field point so that they enter the disperser with the same incident angle, (ii) a dispersive element: a grism; (iii) a dioptric camera, which refocuses the dispersed image on the detectors. Fig. 1 and Fig. 2, respectively, show the two possible designs.

<sup>&</sup>lt;sup>1</sup> The total read-out and background noise, summed over the 26 nm of the spectrum, increases with the number of samples and therefore with the resolution. For the very faint stars, the advantages from the larger amount of spectral information is offset by the higher noise levels.

 $<sup>^2</sup>$  The reflectivity of Silver drops very rapidly below  $\simeq 350 \text{ nm}$ 



**Figure 1.** First optical configuration: Offner relay. The spectrograph entrance plane (telescope focal plane) is located in the upper left corner. The RVS focal plane is represented by the ellipse in the lower left corner. The dispersive element, a grating, is ruled on the secondary mirror (centre).



**Figure 2.** Second optical configuration: dioptric system. The spectrograph entrance plane (telescope focal plane) is on the left side of the figure. The RVS focal plane is represented by the thin line on the right of the figure.

In both configurations, a filter blocks the secondary orders and restricts the RVS wavelength range to the adopted domain: [848, 874] nm. The location of the filter has not yet been decided. For the dioptric option, two locations have been proposed: just before the grism or just before the CCD plane. The first option would limit the amount of parasitic light due to secondary reflections on the filter. In the second case the filter would add more effectively to the radiation shielding protecting the detectors.

The spectral dispersion is oriented along the scan direction. The choice of the orientation of the spectra has been partly driven by the shape of the CCD pixels. Because of manufacturing constraints, the pixels are rectangular: narrower in the along-scan direction than in the acrossscan direction (see § 2.3). Therefore, for the same resolution R = 11500 and sampling (the spectra are sampled at 2 pixels per resolution element), the along-scan orientation of the spectra requires a smaller dispersive power for the grism than the across-scan orientation. In this orientation, the scan law (§ 2.5) acts to broaden spectra in the spatial direction, rather than in the spectral (which would lead to a reduction in spectral resolution). The along-scan orientation also ensures that the spectra of stars located close to the upper or lower boundary of the field of view will not extend beyond the edge of the CCDs.

#### 2.3 Focal plane

The Spectro telescope illuminates three different instruments located in two distinct physical planes. The RVS sky-mapper (whose role is described in § 2.3.1) and the photometric instrument are located at the telescope focus. The RVS CCDs are located at the spectrograph focus. As shown in Fig. 3, the RVS sky-mapper (RVSM) field of view precedes that of the RVS detectors (with respect to the scan orientation).

## 2.3.1 Radial Velocity Spectrometer Sky-mapper

Unlike *Hipparcos*, *Gaia* will not rely on an input catalogue. The satellite will continuously scan the sky and the sources will be detected on-board in real time by dedicated instruments. In the case of the RVS, this role will be devolved to the RVSM. Subsequently, in order to save telemetry, only the RVS pixels illuminated by a spectrum are transmitted to the Earth.

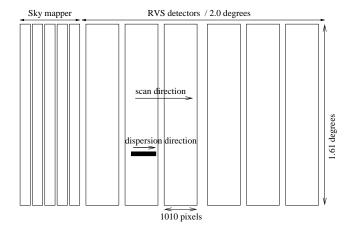
The RVSM is illuminated in undispersed light. In the current baseline<sup>3</sup>, it is composed of 5 CCDs. Four CCDs are illuminated in white light (to maximise the number of photons collected and increase the detection limit) and one is coated with a red filter (see below). In order to follow the scanning motion of the satellite, the 5 CCDs are operated in Time Delay Integration<sup>4</sup> (TDI) mode and read continuously. The data from the white-light illuminated CCDs are analysed on-board in real time by a source detection and centroiding algorithm. The detection diagnostics coming from these CCDs are compared in order to reject false detections (e.g. cosmic rays, CCD defects). The centroiding information from the validated detections is used to predict the location and readout times of the spectra on the RVS detectors.

The wide field of view of the RVSM will allow the detection algorithms to identify fast moving objects (*i.e.* solar system minor bodies and in particular the Near Earth Objects - NEO) and to derive a first estimate of their alongand across-scan motions. The observability of NEOs by *Gaia* is discussed in detail in Mignard (2002).

The fifth CCD will use the same filter as the RVS. This CCD will be used to derive the magnitudes of the sources in the RVS band and to map the sky background with a spatial resolution of  $\sim 30$  arcsec. In fields of high stellar density, the RVS band magnitudes are required to disentangle overlapped spectra during the subsequent processing on the ground (see § 3.2.2).

<sup>&</sup>lt;sup>3</sup> The number of RVSM CCDs is still under consideration and is subject to change.

<sup>&</sup>lt;sup>4</sup> The charges are "continuously" transferred from pixel column to pixel column, in order that they "follow" the sources in their motions across the field of view.



**Figure 3.** Schematic view, projected on the sky, of the RVS skymapper (left) and of the RVS detectors (right). In this figure, the 5 sky-mapper CCDs are represented side-by-side. In practice they could be mixed with other detectors with different functions (e.g. photometric detectors).

# 2.3.2 Spectrograph focal plane

As shown in Fig. 3, the 2.0 degree width of the RVS field of view is filled by 6 CCDs<sup>5</sup>. The design of the RVS focal plane assembly was driven mainly by the issue of the motion of the spectra across the RVS field of view. Because of the *Gaia* scan law (Lindegren 1998), there is a periodic drift of the spectra in the across-scan direction. The transverse velocity of the spectra follows a sine law of period 6 hours (the spacecraft spin period). Its mean semi-amplitude is 0.168 arcsec s<sup>-1</sup>, but this semi-amplitude itself varies on a 6 month timescale from 0.163 to 0.174 arcsec s<sup>-1</sup> because of the eccentricity of the Earth's orbit. This means that there is a spatial smearing of the spectra, up to  $\simeq$  20 arcsec ( $\simeq$  14 pixels) for a transit across the 2 degree width of the RVS focal plane.

Such spatial smearing is prohibitive in terms of loss of signal-to-noise ratio (since the region from which the spectrum is extracted will be larger and will hence contain more background) and substantially enhances the problems arising from overlapping spectra. Several approaches have been identified and compared to minimise this smearing.

In one approach, a mechanism was envisaged to rotate the detector focal plane to compensate for the transverse motion. Other items that could be actuated instead include the dispersing element or any pair of fold mirrors in the optical path. Besides the inherent complexity, the difficulty with this solution is the requirement that the generation of disturbing torques and variable thermal dissipation within the satellite (which would particularly affect the astrometric measurements) should be kept extremely low.

The second approach is to permit the transverse motion, but to split up the focal plane into smaller detector subunits in the scan direction. The transverse drift per observation (*i.e.* per CCD) is limited by the shorter exposure time per detector. The total number of pixels in the fo-

Table 2. Summary of the RVSM and RVS characteristics. The CCD dimensions and total noise are given for one CCD. The overall efficiency of the RVSM is given for the CCD coated with the RVS filter. The overall efficiency includes the telescope reflectivity, the optics (RVS only), grism (RVS only) and filter transmissions and the CCD quantum efficiency (QE).

	RVSM	RVS
Type of CCD	"classical"	L3 CCD
Operating mode	TDI	TDI
Number of CCDs	5	6
CCD dimensions (pixels)	$336 \times 3930$	$1010\times3930$
CCD dimensions (degrees)	$0.09 \times 1.61$	$0.28 \times 1.61$
Exposure time /CCD (s)	5.5	16.5
Pixel size (microns)	$10 \times 15$	$10 \times 15$
Pixel size (arcsec)	$0.98 \times 1.47$	$0.98 \times 1.47$
CCD total noise (e <sup>-</sup> /pixel)	9	2
CCD QE ( $\lambda = 500 \text{ nm}$ )	66%	
CCD QE ( $\lambda = 700 \text{ nm}$ )	92%	
CCD QE ( $\lambda = 860 \text{ nm}$ )	71%	71%
Filter transmission	85%	85%
Overall efficiency ( $\lambda = 860 \text{ nm}$ )	40%	21%

cal plane, as well as the total exposure time per transit (summed over the smaller detector subunits), is kept unchanged. Assuming 6 CCDs (and 16.5 s crossing time per CCD), the maximum transverse drift per observation is  $\simeq 3$  arcsec ( $\simeq 2$  pixels). This is the technique used in the astrometric payload. The absence of an actuation mechanism is an advantage, but the main consequence of this solution is an increase in the number of readouts for a spectral scan, causing reduced performance because of an increase in the readout noise: the instrument performance is readout-noise limited. This drawback could be minimised through the use of innovative detector technologies (L3CCDs) which exhibit very low readout noise and by careful design of the detector electronics.

The tilt mechanism and the 6 L3CCD configurations yield similar performances. The second option (6 L3CCDs) was ultimately adopted because of its lower technical complexity and failure risk. The characteristics of the RVSM and RVS detectors are summarised in Table 2.

One further possible solution is elegant but presently unproven in the context of the RVS. This would be to move the signal "diagonally" within the detector by means of specialised structures on the CCD itself (2-dimensional clocking), thus compensating for the across-scan drift. This solution could also be effective in compensating for the optical distortion. While this technology still needs to be validated for space applications, it has begun to be used in ground observations (Howell et al. 2003). The use of 2D clocking CCDs for the RVS instrument is under evaluation. This solution will be reconsidered for inclusion in the baseline at the end of phase B1 (end of first quarter 2005).

# 2.3.3 RVS observations

The RVS will be operated in TDI scan mode. Therefore, the raw RVS observations will appear as a "never-ending" strip of (spectrally) dispersed sky. However, in order to save on

 $<sup>^5</sup>$  The number of RVS CCDs is still under consideration and is subject to change.



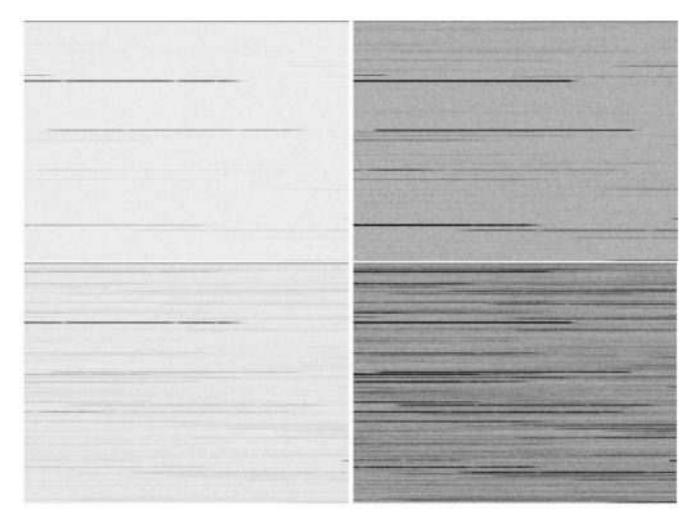


Figure 4. Simulated Gaia-RVS images for high Galactic latitudes (top) and  $|b| \le 5^{\circ}$  (bottom), in linear scale (left) and in "thresholded" linear scale (right). The images are generated for 1 transit of the focal plane of 6 CCDs, each with a readout noise of  $2e^-$ .

the telemetry budget, only the parts of the raw observations containing spectra will be downloaded to the Earth.

Fig. 4 shows snapshots of simulated raw RVS observations for high (top) and low Galactic latitudes (bottom). The images on the left and on the right contain the same stars and only differ by the luminosity scales used to code the number of photo-electrons recorded per pixel (and per transit). The left-hand side images are coded with an inverse linear luminosity scale. In the right-hand side images, the pixels whose intensities are in the range [1, 125]  $e^-$  are coded with an inverse linear luminosity scale and the pixels which exceed 125  $e^-$  are coded in black.

These images have been generated taking into account the main RVS characteristics: spectral resolution, instrumental throughput efficiency, filter function, spatial and spectral point-spread-function (PSF), detector pixel dimensions, photon noise, readout noise, a model for the Zodiacal light contribution and the spatial smearing due to the scan law. The images have been generated down to V=20 using the star density counts as function of Galactic latitude from Table 6.6 of the ESA (2000) report and the distribution of spectral types as given in their Table 6.4. The star positions have been generated randomly for this

assumed stellar density. Spectra of the appropriate brightness and spectral type have been simulated by scaling model spectra taken from the library of Zwitter, Castelli & Munari (2003, 2004). The RVS field of view simulator is accessible and can be run on-line via the simulator web site: http://www.mssl.ucl.ac.uk/gaia-rvs/simulator.html.

What is immediately clear from the simulated images in Fig. 4 is the effect of the overlapping of spectra in low Galactic latitude fields. Less evident, but partly visible in the right-hand side images, is the number of spectra at low light levels in these images (at the V = 17.5 limit, spectra have accumulated less than 1 photon per pixel per transit). Indeed, the spectra visible on the right-hand side of Fig. 4 are all from stars with  $V \leq 15$ . This emphasises the extent to which the readout noise (2 e<sup>-</sup> per pixel per CCD) dominates the signal at the limiting magnitude, except in the Galactic plane where the dominant background is due to faint stars. Therefore, the derivation of radial velocities at the limiting magnitude will be possible only after the co-adding of all of the scans of a given target taken by the end of the mission. This has critical implications for the data-handling, compression and transmission and rules out the possibility of using lossy compression algorithms in transferring the data to the ground.

In Fig. 4, the background light (here only zodiacal light) displays no spectral signature. This will be the case in all the regions of the sky where the background light surface brightness is uniform on an angular scale of a few arcminutes: the spectral information will be smoothed by the slow variation of this source over the field of view.

The simulated images differ from the actual RVS raw observations in that they do not yet include the effects of pixel to pixel variability within the detector, any cosmetic defects in the detectors, or cosmic rays. In addition, they do not include the "small" effect of spectral and spatial smearing due to the "small" distortions from the telescope plus spectrograph optics, nor the effects of co-adding the signal from several detectors that might not be perfectly aligned. In addition, the spectral catalogue contains only "normal", single stars.

#### 2.4 Calibration strategies

The RVS, as well as the other Gaia instruments, presents several peculiarities with respect to classical ground-based instruments: it will scan the sky continuously with (hopefully) no interruption during the 5 years of the mission; it will observe  $\sim 100-150\times10^6$  stars; each star will be observed a large number of times; the instrument will be extremely optically and mechanically stable. All these items support the idea that the RVS instrument could be self-calibrated using a global iterative approach.

The principle of the global iterative calibration is to use an iteratively self-selected sample of "well-behaved" stars (*i.e.* sufficiently bright; astrometrically, photometrically and kinematically stable over successive observations; of a spectral type well-suited for the wavelength calibration) to derive, iteratively, the radial velocities of the iteratively selected stars, calibrate the wavelength scale and calibrate the instrument response and geometry.

The calibration process will use the information provided by the other Gaia instruments: very accurate source positions, very good knowledge of the satellite attitude and of the magnitudes, colours and atmospheric parameters of the sources. Pre-flight calibrations, as well as ground-based radial velocity standards (selected, for example, from among the Solar-type stars surveyed for extra-solar planets), will be used to initiate the iterative process. With the progress of the mission, Gaia will iteratively select thousands of appropriate standards, which will complement the ground-based standards and will provide a very constrained grid in the spatial and temporal dimensions. Finally, the ground-based standards will fix the zero point of the radial velocities.

The full-precision results will be obtained after completion of the observations and after convergence of the iterative auto-calibration procedure. The final Gaia catalogue should be available a few years after mission end: i.e. around 2017-2020. Intermediate releases, of lower precision than the final catalogue, could be envisaged a few years after launch: e.g.  $\sim 2012\text{-}2014$ .

The procedure described above is presently the baseline for the calibration of the RVS and in particular its wavelength calibration. Studies are also in progress to as-

sess whether complementary techniques could be used. The slit-less, objective-prism-like modus operandi of the Gaia spectrograph prevents the use of standard ground-based calibration techniques, involving lamps or sky lines. The only possibility to mark wavelengths on Gaia spectra is to absorb selective wavelengths. Should it emerge during the RVS final system design that it would be a useful tool to implement, an absorption cell could be inserted in the optical chain, filled with an appropriate absorbing medium able to mark strong and widely spaced absorption lines away from those of major astrophysical relevance. Efforts to identify an absorbing medium appropriate for the Gaia operating conditions are underway (Desidera & Munari 2003; Pernechele & Munari 2003). Alternatively, a bundle of multi-mode optical fibres carrying suitable Bragg gratings, inserted in the collimated beam, could be considered. These alternative ways of wavelength calibrating Gaia spectra would probably be of greater interest in the pre-, during- and post-flight ground-based observations, when the maximisation of the science exposure time and the increase of the accuracy are particularly sought after. Particularly promising in this respect are the fibre Bragg gratings that are suitable for mass production.

#### 2.5 Observation strategy

The Gaia satellite will scan the sky continuously during the 5 years of the mission. As in the case of its precursor *Hipparcos*, a uniform revolving scan has been proposed for *Gaia* and parameters for the scanning law were calculated to produce a smooth sky coverage and achieve the best accuracy on the measurements of the astrometric parameters.

The Gaia Nominal Scanning Law (NSL) is described in Lindegren (1998). Some of its parameters have been modified (Spring 2002) to take into account changes in the payload design due to the change of launcher from Ariane V to Soyouz-Fregat.

Gaia will rotate around its z-axis with a uniform velocity of  $\omega=60$  arcsec s<sup>-1</sup> so that each instrument will scan a great circle on the sky in 6 hours. The rotational axis itself precesses at a constant angle of 50 deg around the direction from the satellite to the centre of the Sun. The mean speed of the rotational z-axis on the sky, in units of the apparent Sun speed, is equal to 4.095; this leads to a mean number of 5.200 (overlapping) precession loops of the z-axis on the sky per year, each loop being covered in  $\sim$  70 days. A complete sky coverage is achieved in one year through motion of the axis of the precession cone (which points towards the Solar centre) along the ecliptic.

The NSL makes it possible to predict the attitude of the satellite as a function of time throughout the mission. Using the attitude parametrisation of Gaia-NSL based on the quaternion formalism derived by Lindegren (2000) and the FORTRAN code he provided (Lindegren 2001), the total number of transits during the assumed 5 year mission (arbitrarily starting from J2000) was computed as function of position on the sky for integer values of Galactic longitude and latitude. The number of transits versus Galactic coordinates is plotted in Fig. 5. A similar figure, showing the number of RVS transits as function of ecliptic coordinates, is presented by Pourbaix & Jancart (2003). According to the position on the celestial sphere, the number of transits for

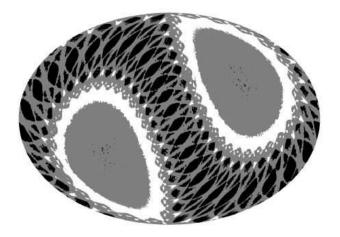


Figure 5. Number of transits through the RVS-field of view versus Galactic coordinates for the 1800 day Gaia mission. There are three "grey" levels:  $\leq 80$  transits (black), between 80 and 120 transits (grey) and  $\geq 120$  transits (white).

the RVS instrument ranges from 54 to 239, with a mean value (averaged over the sky) of 102.

The RVS will provide radial velocities for late type stars up to magnitude  $V\simeq 17-18$  (see § 3.2). The star count model of Chen (1997) has been used by Torra et al. (1999) (updated values are in given in ESA 2000) to evaluate the number of stars to be observed by Gaia as function of magnitude, stellar population, stellar type and Galactic coordinates. The model predicts that 100-150 million stars will be observed up to magnitude V=17-18. Approximately 80% of those stars will belong to the thin disk,  $\simeq 15\%$  to the thick disk and  $\simeq 5-10\%$  to the halo and the bulge. The majority ( $\simeq 70\%$ ) of RVS targets will be G and K type stars.

# 3 STELLAR AND INTERSTELLAR PARAMETERS

#### 3.1 Spectra

In the RVS wavelength range, [848, 874] nm, the spectra of F, G and K type stars are dominated by the ionised Calcium triplet (849.80 nm, 854.21 nm, 866.21 nm). Although the strength of the triplet lines decreases with increasing gravity, it nevertheless remains very strong in dwarf stars: their equivalent widths are larger than 0.3 nm for stars of spectral type F8V to M6V. The triplet is non-resonant and therefore will not be affected by contributions from the interstellar medium. In addition to the Calcium triplet, the RVS spectra of late-type stars will also contain numerous unblended weak lines of astrophysical interest and in particular alpha-elements like Si I or Mg I. In the coolest stars, CN and TiO molecular transitions are visible, but no strong molecular bandhead is present.

In early-type stars, the strongest features are the Paschen lines whose equivalent widths are strongly anticorrelated with gravity. The spectra of hot stars also exhibit some other strong (e.g. Ca II, N I) and weak (e.g. He I, He II) lines.

In addition to the stellar features, the RVS wavelength range contains a diffuse interstellar band  $(862.0~\mathrm{nm})$  which

**Table 3.** Parameters of the 6 representative tracers of Galactic structure plotted in Figure 6.

	Teff	log g	$[\mathrm{Fe/H}]$	$[\alpha/\mathrm{Fe}]$	$v\sin i$
K1 III G5 MS/TO F2 II	4500 5500 7000	2.0 4.0 1.0	0.0 0.0 0.0	0.0 0.0 0.0	5.0 5.0 20.0
B5 MS K1 III F5 MS/TO	15000 4500 6500	4.5 $2.0$ $4.0$	0.0 -1.5 -1.5	0.0 + 0.4 + 0.4	50.0 5.0 20.0

appears to be a reliable tracer of interstellar reddening (see  $\S$  3.5).

Fig. 6 shows examples of synthetic RVS-like spectra for 6 representative tracers of Galactic structure: a K1 III star and a G5 main sequence/turn-off (MS/TO) star of solar metallicity (typical of the disk); an F2 supergiant and a B5 MS star (tracers of spiral structure); a K1 III star and an F5 MS/TO star, both metal-poor (typical of the halo). The parameters of the 6 stars are summarised in Table 3. They have been computed using the VALD atomic data (Piskunov et al. 1995; Ryabchikova et al. 1999; Kupka et al. 1999), the Kurucz atmospheric model (Kurucz 1993a) and N. Piskunov's SYNTH program (Piskunov 1992). All models and spectra have been computed assuming a micro-turbulence velocity of 2 km s<sup>-1</sup> and plane-parallel static atmospheres.

The easy accessibility from the ground of the Gaia wavelength range was one of the factors emphasised by Munari (1999) when proposing the [848 - 874] nm interval, which was at that time also discussed within the GAIA Science Advisory Group as one of the possible wavelength ranges for the mission's spectrograph. This interval is also remarkably clear of telluric absorption, unlike the rest of the  $\lambda \geq 670$  nm far-red optical region.

This allows an intensive observational campaign to be conducted with ground-based telescopes with the aim of deepening our knowledge of this wavelength interval at spectral resolutions equal to, or larger than, the 11 500 foreseen for *Gaia*. By the time that *Gaia* will start to deliver its spectral data, it is to be anticipated that it will become the reference interval for classification and analysis. A wide range of spectroscopic follow-up options will be open to ground-based telescopes, including either a similar observing strategy to that of *Gaia* but to fainter limits, or the extension of the time coverage of variable phenomena.

Inspection of the Asiago Database of Spectroscopic Databases (ADSD) (Sordo & Munari 2003; Sordo & Munari 2004, in preparation), listing 259 atlases for the optical region, returns 12 spectral atlases containing more than 15 objects over the *Gaia* wavelength interval at a resolution larger than 3 000. These 12 atlases offer some insight into the appearance of real stars in this wavelength region, including peculiar types, and the cooler spectral types (F,G,K) that will dominate the field star population at the *Gaia* magnitudes are particularly abundant. The characteristics of the 12 atlases are summarised in Table 4.

No special observational effort appears to be required to assemble new spectral atlases surveying normal stars over the HR diagram in this spectral region. However, more work

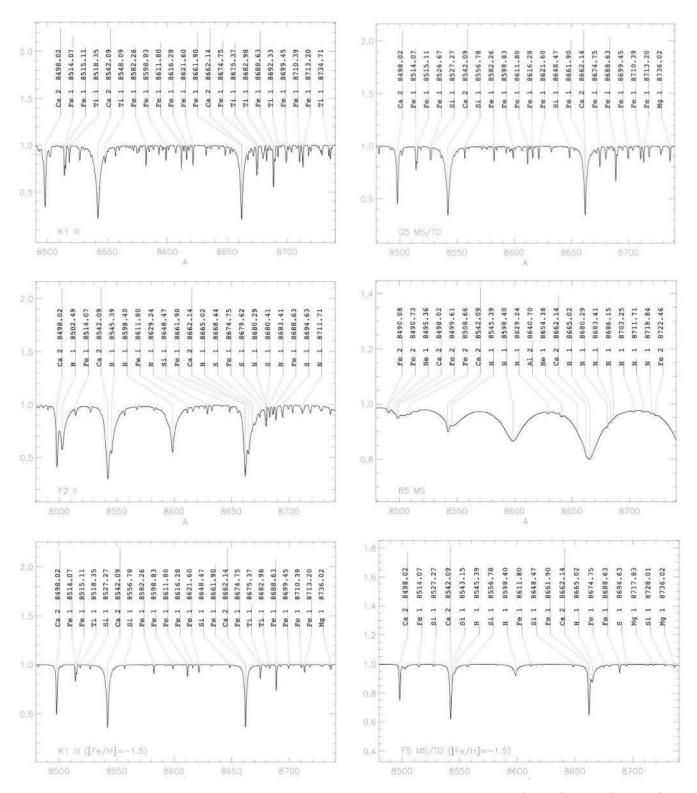


Figure 6. Six examples of RVS-like spectra. The panels show 4 solar metallicity stars: G5 turn-off (top left), K1 III (top right), F2 II (middle left), B5 main sequence (middle right); and two metal-poor stars: F5 turn-off (bottom left) and K1 III (bottom right). See Table 3 for details.

**Table 4.** Spectral atlases with a minimum sample of 15 stars and a resolving power larger than 3 000 over the *Gaia* 848–874 nm spectral range. The columns give the resolving power (R.P.), the number of stars included and the range of their spectral types.

atlas	R.P.	N	spec.
			type
Andrillat, Jaschek & Jaschek (1995)	3000	76	O5-G0,pec
Cenarro et al. (2001)	5000	706	O6-M8
Carquillat et al. (1997)	6500	54	A2-M4,C,S
Valdes et al. (2004)	7200	1273	A0-M8,C,S
Serote Roos, Boisson & Joly (1996)	8000	21	B3-M5
Fluks et al. (1994)	8600	22	MIII
Montes, Ramsey, & Welty (1999)	13000	132	F0-M8
Munari & Tomasella (1999)	20000	130	O4-M8
Marrese, Boschi & Munari (2003)	20000	94	F2-M7
Pavlenko, Marrese & Munari (2003)	20000	24	Carbon
Munari (2003)	20000	17	pec
Montes & Martin (1998)	55000	48	F5-M8

on metal-poor, peculiar and molecular-band stars (M, C, S) can and should be carried out.

#### 3.2 Radial velocities

#### 3.2.1 Performances

The initial motivation for the implementation of a spectrograph on board Gaia was the acquisition of radial velocities. Their determination has, to a large extent, driven the definition and optimisation of the characteristics of the RVS. Throughout the definition phase, studies were conducted to evaluate the performance of the different proposed configurations. Those studies all rely on similar Monte-Carlo approaches to derive the RVS radial velocity precision: cross-correlating a large number of RVS-like spectra, either observed (Munari, Agnolin & Tomasella 2001; David 2001) or synthetic (Katz 2000; Katz et al. 2002; David 2002a,b; Zwitter 2002; Munari et al. 2003) against suitable templates.

Subsequently, the simulations have been re-run to evaluate the performance of the RVS adopted baseline as a function of magnitude and for the 6 representative tracer populations listed in Table 3. In addition, for each of the three spectral types, F2 II, B5 MS and F5 MS/TO, which could present high rotational velocities, two projected rotational velocities have been considered: a "low" and a more "typical" value (see Table 5).

To generate RVS-like observations, Kurucz (1993b) synthetic spectra have been convolved to the RVS spectral resolution, normalised to the star magnitude (according to its atmospheric parameters), sampled (assuming two pixels per PSF full width at half maximum - FWHM) and degraded with photon, background and detector noise, using a simulator of the RVS instrument (Katz 2004, in preparation). The simulations took into account zodiacal light and faint background stars (assuming a total surface brightness of  $V=21.75~{\rm mag~arcsec^{-2}}$ ), the telescope pupil area, the overall instrument efficiency, the exposure time, the spectral profile perpendicular to the dispersion direction and detector noise.

The performances were derived by Monte-Carlo simulations. For each spectral type and magnitude, 1000 or 2000 cross-correlations of RVS-like spectra with Kurucz synthetic templates (convolved at the RVS resolving power) were performed in direct space. In each case, the precision was derived using a robust estimator of the standard deviation of the distribution of (1000 or 2000) estimated radial velocities. After sorting the radial velocities, the standard deviation—was estimated using the following formula:

$$\sigma = \frac{V_{R(0.8415)} - V_{R(0.1585)}}{2}.\tag{1}$$

Here  $V_{R(0.1585)}$  is the  $15.85^{th}$  percentile of the sorted distribution of radial velocities and  $V_{R(0.8415)}$  is the  $84.15^{th}$  percentile of the same distribution. This robust estimator gives low weight to the outliers which appear at the faintest magnitudes (when secondary correlation peaks could be mistaken for the correct correlation peak). Future work will focus on the development of techniques to identify and reject these outliers. The fraction of outliers (i.e. the fraction of estimated radial velocities beyond 3 times the estimated dispersion) is, to a first approximation, a function of the estimated dispersion and of the stellar type. For  $\sigma=5~{\rm km~s^{-1}}$  there are  $\simeq 1.5\%$  and  $\simeq 0\%$  outliers, respectively, in the cases of a G5V star and of a F2 II star. The fractions of outliers become  $\simeq 12\%$  and  $\simeq 7\%$  respectively for  $\sigma=20~{\rm km~s^{-1}}$ .

In these simulations, the distributions of estimated radial velocities exhibit no statistically significant bias.

Many small effects still remain to be taken into account in the full assessment of the RVS accuracy budget. These include optical aberration, CCD charge transfer inefficiency, instrument and wavelength calibration. In order to account for these missing effects, a 40% explicit error margin was added to the RVS performances. The radial velocity performances, for single observations and at the end of the mission (after combining the 102 observations collected over the 5 years of the mission), are presented in Table 5. It is likely that the second order effects will become very significant or even dominant for sufficiently bright stars, for which the present simulations give  $1 \text{ km s}^{-1}$  or better performance. For this reason, no values below  $\sigma = 1 \text{ km s}^{-1}$  are given in Table 5. Above  $\sigma \simeq 30\text{-}40 \text{ km s}^{-1}$  the performance degrades very rapidly as function of magnitude and the estimation of the performance becomes imprecise. As a consequence, no values above  $\sigma = 35 \text{ km s}^{-1}$  are given in Table 5.

The precisions given in Table 5 have been evaluated for the average number of observations per star, namely 102 transits. As described in § 2.5, the number of epochs of observation will vary with Galactic coordinates. As a consequence, the end of mission performances and the range of magnitude probed by the RVS will also vary with Galactic coordinates. As an example, for a G5 MS/TO and for the minimum (54 transits), average (102 transits) and maximum (239 transits) number of observations, a precision of  $\sigma \simeq 16~{\rm km~s^{-1}}$  is obtained respectively for  $V \simeq 16.65,$   $V \simeq 17~{\rm and}~V \simeq 17.45~{\rm mag}.$ 

Another parameter which varies with Galactic coordinates and which will impact on the RVS performance is the stellar density. This is discussed in the next section.

**Table 5.** Precision (one sigma error) of the RVS instrument in the derivation of radial velocities as a function of magnitude, for a single observation (top) and at the end of the mission (102 observations: bottom). The performances are expressed in km s<sup>-1</sup>.

							Single	transit				
	[Fe/H]	$v \sin i$						V				
	, ,	$({\rm km~s^{-1}})$	9	10	11	12	13	13.5	14	14.5	15	15.5
K1 III	0.0	5	≤ 1	≤ 1	≤ 1	1.1	2.3	3.1	4.7	7.2	11.5	34.9
G5 MS/TO	0.0	5	$\leq 1$	$\leq 1$	1.2	2.1	4.4	6.3	9.7	19.7	> 35	> 35
F2 II	0.0	20	$\leq 1$	1.3	2.3	4.3	9.3	14.4	24.3	> 35	> 35	> 35
F2 II	0.0	50	1.3	2.1	3.6	6.5	13.8	21.2	33.4	> 35	> 35	> 35
B5 MS	0.0	50	14.8	25.0	> 35	> 35	> 35	> 35	> 35	> 35	> 35	> 35
B5 MS	0.0	150	18.3	31.1	> 35	> 35	> 35	> 35	> 35	> 35	> 35	> 35
K1 III	-1.5	5	$\leq 1$	$\leq 1$	1.1	1.8	3.6	5.0	7.5	11.7	26.8	> 35
F5 MS/TO	-1.5	20	1.2	1.9	3.2	5.8	12.3	24.3	> 35	> 35	> 35	> 35
F5 MS/TO	-1.5	50	2.1	3.4	5.6	10.7	22.3	> 35	> 35	> 35	> 35	> 35
						Mission (	102 tran	ısits - av	orogo co	(02		
					IV.	TISSIOII (			erage ca	se)		
	[Fe/H]	$v \sin i$	V									
		$(\mathrm{km}\ \mathrm{s}^{-1})$	12	13	14	15	15.5	16	16.5	17	17.5	18
K1 III	0.0	5	≤ 1	≤ 1	$\leq 1$	1.1	1.6	2.6	3.8	6.2	10.6	25.5
G5 MS/TO	0.0	5	$\leq 1$	$\leq 1$	$\leq 1$	2.1	3.4	5.0	8.3	16.0	> 35	> 35
F2 II	0.0	20	$\leq 1$	$\leq 1$	2.0	4.8	7.6	12.6	20.8	> 35	> 35	> 35
F2 II	0.0	50	$\leq 1$	1.3	3.1	7.5	11.4	18.0	29.9	> 35	> 35	> 35
B5 MS	0.0	50	8.2	18.6	> 35	> 35	> 35	> 35	> 35	> 35	> 35	> 35
B5 MS	0.0	150	10.0	23.5	> 35	> 35	> 35	> 35	> 35	> 35	> 35	> 35
							0.5	4.1	0.0	10.0	00.4	. 05
K1 III	-1.5	5	$\leq 1$	$\leq 1$	$\leq 1$	1.7	2.5	4.1	6.3	10.3	23.4	> 35
K1 III F5 MS/TO	-1.5 -1.5	$\frac{5}{20}$	$\leq 1$ $\leq 1$	$\leq 1$ $1.1$	$\leq 1$ $2.6$	$\frac{1.7}{6.1}$	$\frac{2.5}{9.5}$	$\frac{4.1}{17.3}$	> 35	> 35	23.4 > 35	> 35 > 35

# 3.2.2 Crowded regions

Because the RVS is an integral field spectrograph, some degree of spectral overlap is unavoidable, even in regions with a low stellar density. Consequently, the background to be subtracted from any spectrum consists not only of the smooth zodiacal light contribution but also of discrete jumpy spectral tracings of (partially) overlapping stars. Fig. 7 depicts examples of such background spectra: on the left, a low density region (1000 stars/deg² with V < 17) typical for the "high" Galactic latitudes ( $|b| \geq 30^{\circ}$ ) and on the right, a higher density region (6000 stars/deg² with V < 17) representative of the range of latitudes:  $5^{\circ} \leq |b| \leq 10^{\circ}$ .

Overlaps of the brightest background stars are rare and occur only on a small number of transits. Their contribution to the overall background is not, however, negligible and their spectral lines can degrade the accuracies of the radial velocity or other parameters. Fig. 7 shows the background accumulated over the whole mission, excluding transits with overlapping stars brighter than V = 14. The loss of integrated signal corresponding to the rejection of the transits containing "bright" contaminating stars is acceptably low. Bright (V < 14) overlappers are present in  $\sim 3\%$  (Galactic halo) or  $\sim$  13% (Galactic plane) of all transits. The bottom panels of Fig. 7 plot individual contributions from the ten strongest overlapping stars fainter than V = 14 while the top panels show the background signal which is the sum of these 10 and several fainter contributors. The fluxes are given in units of the flux from a V=17 K1 V star integrated over the whole mission (102 transits). Note that the accumulated background is very smooth. Lines from individual overlapping stars become diluted by the continuum contributions of other overlapping stars in the same and other transits.

The background can be very well modelled from information that is available from Gaia's astrometric and photometric measurements (stellar positions, magnitudes, rough spectral types and velocities of overlapping stars). In Fig. 7 it is assumed that stellar positions and magnitudes are accurately known which is certainly true given the excellent astrometric accuracy combined with the photometric and star mapper measurements. Also, spectral information could be derived from photometric observations: in Fig. 7 a mismatch of 250 K in temperature and 0.5 dex in metallicity and gravity are assumed. We note that this is conservative, as the final errors on these parameters are expected to be roughly half these values. If, in addition, some knowledge (provided by the RVS) on the radial velocities of the overlapping stars is assumed the overall background can be modelled.

From the above paragraph, it would appear that the radial velocities are simultaneously necessary to model both the background and the unknown information one wants to extract from the spectra. One possible approach to solve this problem is to proceed in an iterative way. At each iteration, the "stacked" spectra are analysed, one by one, from the brightest to the faintest star. The analysis of each spectrum is made of two consecutive steps: modelling and subtraction of the background and then derivation of the radial velocity. On the first iteration, the background of a given star is modelled using the first estimates of the radial velocities of the sources brighter than this star (which have already been analysed) and using only the level and shape of the

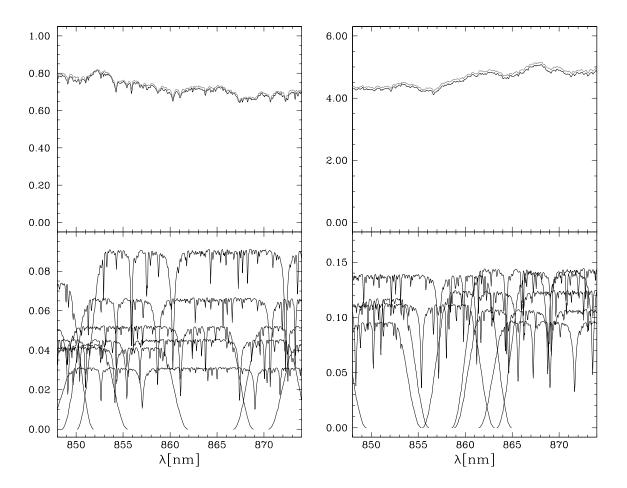


Figure 7. Crowding of stellar spectra in the focal plane of the slitless spectrograph results in spectral overlaps. The left panels depict the typical situation at "high" Galactic latitudes:  $1000 \text{ stars/deg}^2$  with V < 17. The right panels are for a more crowded region near the Galactic plane:  $6000 \text{ stars/deg}^2$  with V < 17. The top panels show the background accumulated over the whole mission (for a spectral tracing width of 2 pixels) if the transits with overlaps of the stars brighter than V = 14 are omitted. The true background is plotted in black (lower line) and the one recovered from the astrometric and photometric information from other instruments aboard Gaia in grey (upper line). The bottom panels show, in the same ordinate units as in the upper ones, the contribution to the background of the ten brightest stars fainter than V = 14. Ordinates are fluxes in units of the flux from a V = 17 K1 V star integrated over the whole mission.

continua of the fainter stars (whose radial velocities have not yet been estimated). At the end of the first iteration, an estimate of the radial velocity of each of the "stacked" stars has been derived. The process is then iterated. The new or refined estimates of the radial velocities are used to refine the background modelling which, in turn, is used to refine the estimates of the radial velocities.

The simulations performed to compute Fig. 7 assume that the radial velocities are known with precisions of:  $\sigma V_R = 2 \text{ km s}^{-1}$  at V = 14 and 20 km s<sup>-1</sup> at V = 17 (this simulates an intermediate stage of the iterative process). The result of the background modelling (grey lines in the top panels of Fig. 7) is encouraging. First tests based on the background modelling technique (Zwitter 2003) inspire confidence that radial velocities can be obtained from such overlapping spectra with moderate degradation of performance up to  $\simeq 20~000~\text{stars/deg}^2$  with V < 17.

The information obtainable from crowded regions will be worse than for sparsely populated ones. Nevertheless, the

overlapping stars degrade the RVS accuracy mainly by increasing the background shot noise level. Such a conclusion is justified if one can rely on the accurate knowledge of the flux throughput of the instrument and on accurate spectral modelling of the background stars. In forthcoming studies, we intend to investigate this issue in detail and, in particular, to implement and test the full iterative analysis process.

# 3.3 Atmospheric parameters and individual abundances

Gaia will rely on a large variety of observables to classify and parameterise the stars (Bailer-Jones 2002, 2003): distances (and therefore absolute magnitudes), 5 broad photometric bands, 11 medium photometric bands and R=11500 spectra over the wavelength range [848, 874] nm. In this section we focus on the information contained in the spectroscopic data.

The spectral richness of the RVS wavelength range gives

a broad diversity of line absorption responses which vary with  $T_{\rm eff}$ ,  $\log g$  and  $[Z/Z_{\odot}]^6$ . As a consequence, the RVS spectral range contains all the required information to derive the stellar atmospheric parameters.

At present, the spectroscopic determination of the atmospheric parameters requires the micro-turbulence velocity to be constrained. In the future, this *ad hoc* parameter will be replaced by a 3-dimensional description of the stellar atmospheric structure (temperature, pressure *etc.*) and velocity field.

Many methods have been developed to determine stellar atmospheric parameters from spectra. One widely-used technique is detailed stellar spectral analysis. The effective temperature and surface gravity are constrained by requiring that abundances derived from different lines be independent of the line excitation potential (for a given element) and of the element ionisation stage. This method (even fully automated) is not suited for the analysis of RVS spectra because of the absence of sets of weak unblended lines from given elements in two different ionisation stages, which would allow the ionisation equilibrium to be constrained. Alternative techniques have been developed based on automatic comparison using the minimum distance method between measured and synthetic spectral quantities such as the equivalent widths (EW) of strong lines (Thevenin & Foy 1983). These methods also require a "good" S/N ratio, which reduces their performance for faint stars.

For this reason, different techniques have been developed in order to analyse spectra of moderate to low S/N ratios. In these techniques, the set of EW values have been replaced by the whole spectrum (Cayrel et al. 1991; Thevenin & Jasniewicz 1992; Katz et al. 1998; Allende Prieto 2003), diminishing the effect of a low S/N ratio and producing results comparable to detailed analysis based on spectra with high resolution. Thevenin, Bijaoui & Katz (2003) have used a grid of synthetic spectra to explore the influence of resolution on the recovered atmospheric parameters of late-type stars. They concluded that resolutions R = 12000 and higher were appropriate to recover the three main atmospheric parameters. Soubiran (2001) has evaluated the performance of the comparison of full spectra using the minimum distance method in the RVS wavelength range and assuming a resolving power half that adopted for Gaia. She degraded the observed spectra from the library of Cenarro et al. (2001) to a S/N=20 and compared each spectrum to the rest of the library one-by-one. The parameters of the stars were recovered with precisions of:  $\sigma(T_{eff}) = 275 \text{ K}, \ \sigma(\log g) = 0.36,$  $\sigma([Fe/H]) = 0.22$  dex. A S/N=20 by the end of the mission corresponds to  $V \simeq 14.5$  for a K1III star,  $V \simeq 14.0$  for a G5V star and  $V \simeq 13.5$  for an F2 II star. Because of its higher resolution, the RVS performances are expected to be better than this.

Another way to extract the atmospheric parameters is to use Neural Networks (Bailer-Jones 2000). Tests have demonstrated (Bailer-Jones 2003) that using the R=5800 li-

<sup>6</sup> The variation of line intensity responses with the atmospheric parameters are well detailed in Table 4 of Cayrel & Jugaku (1963).

brary  $^7$  of Cenarro et al. (2001),  $T_{\rm eff}$  can be determined to within 5%,  $\log g$  within 0.5 (solar metallicity) to 1.0 (metal poor stars) and [Fe/H] within 0.3 dex.

Up to  $V \simeq 14-15$ , the atmospheric parameters will be derived using not only the spectroscopic observations, but also (and jointly) the astrometric and photometric data. The global precision of the atmospheric parameters from Gaia should be higher than that estimated from the spectroscopic information alone, which is presented here. The astrometric and photometric observations will also allow the evaluation of the atmospheric parameters of the fainter stars.

For the brightest stars, measurements of equivalent widths and/or synthetic profile fitting will allow the extraction of individual abundances from RVS spectra. The elements concerned are mainly Fe, Ca, Mg and Si for the late-type stars F, G, and K. The abundances of other elements like N can be derived in hotter stars such as A-type stars. For the cooler stars, K and M types, molecular bands can provide information on C, N or TiO abundances. This raises the possibility of investigations into the chemical evolution of the Galaxy. Due to the quality of the spectra, the error on the deduced stellar abundance of a chemical element depends on the resolution, the S/N and the spectral sampling on the CCD. Using Cayrel's formula (Cayrel 1988), the error on an equivalent width measurement of 0.005 nm at a resolution R = 11500 and for S/N = 50, is 0.0015 nm, corresponding, for this weak line, to an error of 0.13 dex on the abundance. A S/N=50 (at the end of the mission) corresponds to  $V \simeq 13$  for G5V and K1III stars and to  $V \simeq 12$ for an F2 II star.

The RVS spectra will be used, jointly with the photometric and astrometric data, to determine the atmospheric parameters of about  $10-25\times 10^6$  stars down to  $V\simeq 14-15$ . They will also permit the extraction of individual abundances in  $2-5\times 10^6$  stars down to  $V\simeq 12-13$ .

#### 3.4 Rotational velocities

The analysis of stellar spectra obtained with Gaia-RVS will, in addition to other stellar characteristics, enable the determination of the projected rotational velocity  $(v \sin i)$  of individual stars. The impact of the Gaia contribution to stellar rotation astrophysics depends primarily on the precision obtained on  $v \sin i$  and on the dependence of this precision on stellar type and magnitude.

The spectroscopic determination of  $v \sin i$  is based on the rotational broadening of spectral lines. Analysis methods used to determine  $v \sin i$  include fitting by least squares, measurement of FWHM, estimations of the width of the correlation peak, deconvolution and Fourier transforms.

In order to estimate the precision of rotational velocities obtained from Gaia spectra, we performed simulations on synthetic Kurucz stellar spectra and used the simple least squares fit method. The simulations and results presented here are for the RVS spectral resolution  $R\!=\!11500$  (for results obtained for  $R\!=\!5000$  - 20000 see Gomboc (2003)).

The simulation starts by choosing a stellar type (i.e. a spectrum with given  $T_{\rm eff}$ ,  $\log g$ , [Fe/H],  $[\alpha/Fe]$ ) and original

 $<sup>^7\,</sup>$  The median signal to noise ratio per resolution element of the library is 85.

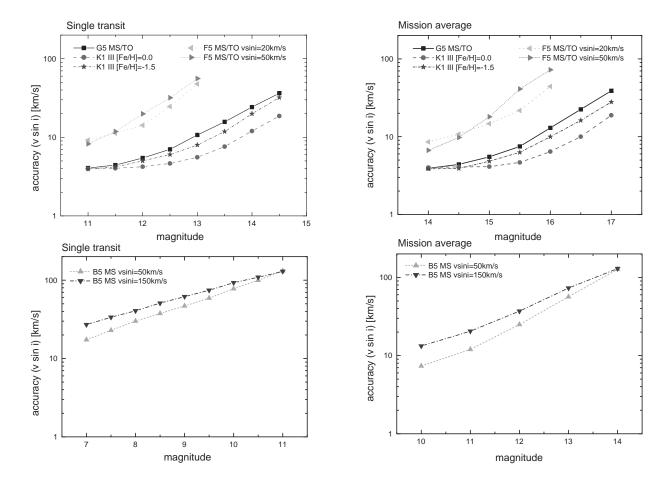


Figure 8. Precision of  $v \sin i$  for a single stellar transit over the RVS focal plane (left) and at the end of the mission (right) as a function of magnitude and for the stellar types: K1 III, G5 MS/TO and F5 MS/TO (top) and B5 MS (bottom).

 $v\sin i$ . This spectrum is used to generate RVS-like spectra using the RVS simulator described in § 3.2. Afterwards, comparisons between simulated and noise-free templates with various  $v\sin i$  are performed and the template with the minimum square deviation is taken as the best fit. The precision is taken to be the standard deviation of the differences between the original and recovered  $v\sin i$  (number of trials N=1000).

To estimate the *Gaia*-RVS capabilities, simulations were performed for 5 out of the 6 stellar types representative of the different Galactic populations listed in Table 3. The F2 supergiant was not considered in this study, because the macro-turbulent motion in its pulsating atmosphere affects the line profiles, which cannot therefore be used to estimate the rotational velocity.

As the first step towards a detailed and more accurate estimation of the precision of  $v \sin i$  determinations, only single parameter fits were performed. This is the best-case scenario, because it is assumed that the other stellar parameters (T<sub>eff</sub>, log g, [Fe/H],  $[\alpha/Fe]$ ,  $V_r$ ) are exactly known and in the fitting procedure spectra which differ only in  $v \sin i$  are used. The results are presented in Fig. 8. Precisions of  $\sigma_{v \sin i} \simeq 5 \text{ km s}^{-1}$  should be obtained at the end of the mission for  $V \simeq 15$  late-type stars. For B5 MS stars, precisions

(at the end of the mission) of  $\sigma_{v \sin i} \leq 10\text{-}20 \text{ km s}^{-1} \text{ should}$  be obtained up to  $V \simeq 10\text{-}11$ .

The distributions of estimated  $v\sin i$  exhibit a small bias of a few kilometres per second at the "bright" end, which increases at fainter magnitudes. The errors due to the bias are included in the performances presented in Fig. 8.

In practice, the estimates of  $T_{\text{eff}}$ ,  $\log g$ , [Fe/H],  $[\alpha/Fe]$ and  $V_r$  obtained by Gaia will have their own uncertainties, which will influence the precision of the  $v \sin i$  determination. To estimate the influence of those uncertainties on the precision of the estimated rotational velocity, similar simulations were performed but the original spectrum was fitted with spectral templates that had one of the parameters (T<sub>eff</sub>,  $\log g$ , [Fe/H],  $[\alpha/Fe]$ , or  $V_r$ ) offset from its true value. Results are still preliminary, but suggest that an offset of 0.5 in  $\log g$  does not substantially influence the precision of the estimated rotational velocity; the precision of  $v \sin i$  is not significantly affected by a mismatch of up to 125 K in effective temperature; errors of 0.1 dex in metallicity do not seem to affect significantly the precision of  $v \sin i$ , while a 0.25 dex mismatch leads to degraded rotational velocities  $(\sigma > 10 \text{ km s}^{-1})$ ; and errors in radial velocity of 10 km s<sup>-1</sup> lead to errors in rotational velocities of more than  $10 \,\mathrm{km \ s^{-1}}$ .

The results presented in Fig. 8 are considered only as

a first order estimation of the performance of Gaia in the field of stellar rotation determination. These results were obtained using synthetic stellar spectra and, therefore, modelling uncertainties and chemical composition peculiarities were not taken into account. Furthermore, in regions of high stellar density, the effect of crowding will also undoubtedly degrade the determination of the rotational broadening of spectral lines. The preliminary results also show that the effects of the combined errors in template parameters ( $T_{\rm eff}$ ,  $\log g$ , [Fe/H],  $[\alpha/Fe]$ ,  $V_r$ ) are not easy to predict. While all the results presented here were obtained by single parameter  $(v \sin i)$  fitting, more accurate estimations of the performance will be obtained in multi-parameter fitting simulations.

The performance of other analysis techniques will also be assessed in future work. For example, cross-correlation techniques would allow us to disentangle the combined effect of rotational broadening, [Fe/H] and radial velocity, which respectively influence the width, the area and the position of the cross-correlation function. Moreover, using a box-shaped template would make the determination less sensitive to spectral mismatch.

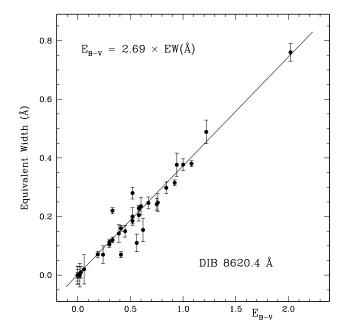
#### 3.5 Interstellar reddening

Gaia will accurately place all the observed stars in a 3-dimensional representation of the Galaxy. The synergy between spectroscopy and multi-band photometry will allow Gaia to quantify the reddening law and the amount of extinction of interstellar origin in any direction and to any distance through the Galaxy. Continuity of the reddening along the line of sight will serve to isolate deviant points during the iterative building of the 3D Galactic extinction map. Most of these deviant points will either be due to the use of incorrect models for the intrinsic energy distributions or to circumstellar absorption.

A direct probe, independent of the modelling of the intrinsic energy distribution of the targets, would be valuable in calibrating the zero point and scale of the 3-dimensional extinction map during its iterative assembly, in distinguishing between the alternative causes of deviation mentioned above and in providing some clues to the nature of the intervening absorbing material.

Gaia spectroscopy can provide such a direct probe. This is not in the form of atomic absorption lines, however, because no sufficiently strong resonant line lies within the Gaia spectroscopic interval. Such atomic absorption lines would trace the gaseous phase of the interstellar/circumstellar medium and a gas-to-dust ratio would have to be adopted in order to convert it into extinction. The interstellar medium, however, also manifests itself on spectra with absorption features other than those of atomic origin. These are termed diffuse interstellar bands (DIBs).

One such DIB lies right at the centre of the *Gaia*-RVS spectral range, at 862.0 nm, where no significant spectral features appear in the spectra of hot stars (cf. Munari & Tomasella 1999) - the best suited to trace interstellar absorption to the furthest distances. Munari (1999) was the first to investigate this band in detail and found a remarkable correlation of its intensity with reddening. Such a relation is unusual among DIBs, which on average show only a mild correlation with reddening (Herbig 1995). Munari



**Figure 9.** Correlation between the equivalent width of the 862.0 nm DIB and reddening for stars covering a range of Galactic coordinates as observed in Asiago (from Munari 2000).

(2000) enlarged the sample of investigated stars (covering a larger range of Galactic coordinates and distances) and reinforced the evidence for such a relation, which takes the form (Fig. 9):

$$E_{B-V} = 26.9 \times E.W.(\text{nm}) \tag{2}$$

were E.W. is the equivalent width of the 862.0 nm DIB. Such a tight relation with reddening suggests a direct association between the carrier(s) of the 862.0 nm DIB and the dust phase of the interstellar medium. The dimensions and composition of interstellar dust grains change through the Galaxy leading to the known effects of the 217.5 nm bump or the ultraviolet slope of the extinction law. It may be expected that these changes will affect the slope of Eq.(2) which can be generalised to cylindrical coordinates mapping the 3D structure of the Galaxy as:

$$E_{B-V} = \alpha(l, b, D) \times E.W.(nm) \tag{3}$$

Both the extinction and reddening law map the solid phase of the interstellar medium (i.e. the dimensions and chemistry of the dust grains). The nature of the DIB carriers is still unknown, even if they are generally believed to be associated with complex molecules, and this makes DIBs potentially useful to trace (at least in part) the gaseous phase of the interstellar medium. It may be expected that regions deviating from the dust characteristics of the diffuse interstellar medium (as in some circumstellar nebulae and winds) will display a 862 nm DIB deviating from the above relation. In this regard, while Gaia photometry will be by far the main tool for the derivation of reddening information, the 862 nm DIB appears to be a useful probe of the conditions within the interstellar medium. For example, HD 62542 has one of the most extreme ultraviolet extinction curves known, featuring a very broad, shortwardly-displaced 217.5 nm bump and an extremely steep far-UV rise. In spite of an estimated  $E_{B-V}$ =0.35, it does not show appreciable signs of classical 578.0, 579.7, 627.0, 628.4, and 661.4 nm DIBs in its optical spectrum (Snow et al. 2002).

An 862.0 nm DIB as weak as that corresponding to  $E_{B-V}$ =0.10 should be easily identifiable on the R=11500 Gaia-RVS spectra of all early type stars with S/N $\geq$ 100. This will provide a great opportunity for the direct probing of the interstellar and circumstellar medium, independent of the photometric approach. Additional, dedicated, ground-based observations to investigate the nature and behaviour of the 862 nm DIB in more detail prior to the Gaia launch are to be encouraged.

#### 3.6 Data archiving, calibration and analysis

The development of the on-ground data archiving and processing system is one of the key challenges during the preparation for the RVS and for Gaia in general. During the 5 years of the mission, Gaia will collect about 10-15 billion spectra of  $\simeq 100 - 150$  million stars as well as astrometric data and multi-band photometry for about a billion stars. The calibration and analysis of such a huge amount of heterogeneous data (all spectral types and luminosity classes including variable and peculiar stars, single and multiple systems, very different field stellar densities and therefore levels of crowding, different temporal sampling as a function of Galactic coordinates, three different instruments), as well as the particular observing mode (continuous and repeated scans of the celestial sphere) require new, robust and fully-automated methods to be developed. The RVS data will not be processed independently of the astrometric and photometric observations: on the contrary, specific methods will be developed to calibrate and analyse the Gaia data, as much as possible, in a global way using the whole body of information provided by the three instruments.

The "Gaia Database Access and Analysis Study" (GDAAS), (2000-2004), is developing a prototype of the data archiving and processing system. At the time of writing, mid-2004, a prototype of the data model and archiving system is in place and several algorithms, including the astrometric global iterative solution, have been implemented and tested (Figueras et al. 2003). By the end of the study, more than 20 algorithms, including a non-optimised derivation of the radial velocities, should be in place. The GDAAS activity will be replaced from  ${\sim}2006$  by the development of the full Gaia archiving and analysis system.

In parallel with the development of data processing tools, studies are in progress to improve our knowledge of atomic and molecular data, to refine the computation of stellar models and synthetic spectra and to build libraries of observed reference spectra. All this information will be used by the calibration and analysis processes and their quality will be directly reflected in the accuracy of the derived stellar and interstellar parameters.

#### 4 CONCLUSIONS

The Radial Velocity Spectrometer is a  $2^{\circ} \times 1.61^{\circ}$  integral field spectrograph observing in TDI scan mode over the wavelength range [848, 874] nm with a resolving power  $R = \lambda/\Delta\lambda = 11$  500. The RVS will provide a rich harvest

of stellar and interstellar parameters: radial velocities up to magnitude  $V \simeq 17\text{-}18$ , rotational velocities with precisions for late type stars of  $\sigma_{v\sin i} \simeq 5$  km s<sup>-1</sup> at  $V \simeq 15$ , individual element abundances (for stars with  $V \leq 12\text{-}13$  mag) and interstellar reddening. It will also contribute, together with the astrometric and photometric data, to the determination of the atmospheric parameters of stars brighter than  $V \simeq 14\text{-}15$ . Moreover, many stellar processes will imprint their distinctive signatures in the RVS spectra: e.g. pulsation and variability, mixing, accretion, winds and mass loss. Finally, the large number of epochs of observation will make it possible to detect and characterise binary and multiple stellar systems as well as periodic and transient phenomena

During the two years 2001-2002, the RVS preparation studies were mainly focused on the definition of the instrument scientific case and on the comparison of the performance of the different possible configurations. These studies converged in late 2002 with the selection of the baseline concept. The RVS work is now mainly devoted to (i) the optimisation and development of the instrument design, (ii) the simulation of more realistic RVS-like spectra which will be used to refine the evaluation of the performance of the spectrograph and (iii) the definition and development of the on-board and on-ground data processing algorithms.

# ACKNOWLEDGMENTS

We would like to thank the ESA and industry teams preparing the *Gaia* mission for their active and efficient support. We are very grateful to R. Kurucz, F. Kupka, N. Piskunov and the VALD people for making their software packages and molecular data available to the community. DK, FT, FA, CT and SM acknowledge financial support from CNES. MIW acknowledges financial support from PPARC. We are grateful to our referee, G. Gilmore, for useful comments which improved the quality of the manuscript.

# REFERENCES

Allende Prieto C., 2003, MNRAS, 339, 1111

Andrillat Y., Jaschek C., Jaschek M., 1995, A&AS, 112, 475

Bailer-Jones C. A. L., 2000, A&A, 357, 197

Bailer-Jones C. A. L., 2002, Ap&SS, 280, 21

Bailer-Jones C. A. L., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy, Science and Technology. Astron. Soc. Pac., Monte-Rosa, p199

Binney J. J., Dehnen W., Houk N., Murray C. A., Penston M. J., 1997, in ESA, ed., ESA SP-402: Hipparcos - Venice '97. ESA, Venice, p473

Carquillat M. J., Jaschek C., Jaschek M., Ginestet N., 1997, A&AS, 123, 5

Cayrel R., 1988, in Cayrel de Strobel G., Spite M., eds, Proc. IAU Symp. 132, The Impact of Very High S/N Spectroscopy on Stellar Physics. Kluwer Academic Publishers, Paris, p345

Cayrel R., Jugaku J., 1963, Annales d'Astrophysique, 26, 495

- Cayrel R., Perrin M.-N., Barbuy B., Buser R., 1991, A&A, 247, 108
- Cenarro A. J., Cardiel N., Gorgas J., Peletier R. F., Vazdekis A., Prada F., 2001, MNRAS, 326, 959

Chen B., 1997, ApJ, 491, 181

David M., 2001, RVS-MD-001, ESA report

David M., 2002a, RVS-MD-002, ESA report

David M., 2002b, RVS-MD-003, ESA report

Desidera S., Munari U., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy, Science and Technology. Astron. Soc. Pac., Monte-Rosa, p85

ESA, 2000, GAIA:Composition, Formation and Evolution of the Galaxy. ESA, Technical report ESA-SCI(2000)4

Favata F., Perryman M., 1995, ESA SP, 379, 153

Figueras F., Torra J., Serraler I., Masana E., Luri X., Jordi C., Llimona P., Pérez P., 2003, UB-GDAAS-TN-020, ESA report

Fluks M.A., Plez B., The P.S., de Winter D., Westerlund B.E., Steenman H.C., 1994, A&AS, 105, 311

Gerbaldi M., Gómez A., Grenier S., Turon C., Faraggiana R., 1989, Messenger, 56, 12

Gomboc A., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy, Science and Technology. Astron. Soc. Pac., Monte-Rosa, p285

Herbig G. H., 1995, ARA&A, 33, 19

Howell S. B., Everett M. E., Tonry J. L., Pickles A., Dain C., 2003, PASP, 115, 1340

Katz D., 2000, PhD thesis, Paris VII University

Katz D., Soubiran C., Cayrel R., Adda M., Cautain R., 1998, A&A, 338, 151

Katz D., Viala Y., Gomez A., Morin D., 2002, in Bienaymé O., Turon C., eds, EAS Pub. Ser. Vol. 2, GAIA: A
European Space Project. EDP Sciences, Les Houches, p63
Kupka F., Piskunov N., Ryabchikova T. A., Stempels H. C.,
Weiss W. W., 1999, A&AS, 138, 119

Kurucz R., 1993a, ATLAS9 Stellar Atmosphere Programs and 2 km/s grid. Cambridge, Mass.: Smithsonian Astrophysical Observatory, CD-ROM No. 13

Kurucz R., 1993b, SYNTHE Spectrum Synthesis Programs and Line Data. Cambridge, Mass.: Smithsonian Astrophysical Observatory, CD-ROM No. 18

Lindegren L., 1998, SAG-LL-014, ESA report

Lindegren L., 2000, SAG-LL-030, ESA report

Lindegren L., 2001, SAG-LL-035, ESA report

Marrese P. M., Boschi F., Munari U., 2003, A&A, 406, 995 Mayor M., Duquennoy A., Grenon M., Turon C., Crifo F., Imbert M., Maurice E., Prevot L. et al., 1989, Messenger, 56, 12

Mignard F., 2002, A&A, 393, 727

Montes D., Martin E. L., 1998, A&AS, 128, 485

Montes D., Ramsey L. W., Welty A. D., 1999, ApJS, 123, 283

Munari U., 1999, Baltic Astronomy, 8, 73

Munari U., 2000, in Porceddu I., Aiello S., eds, Proc. Ita. Phys. Soc. Conf. Vol. 67, Molecules in Space and in the Laboratory. Carloforte, p179 (also astro-ph/0010271)

Munari U., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy, Science and Technology. Astron. Soc. Pac., Monte-Rosa, p227

Munari U., Tomasella L., 1999, A&AS, 137, 521

Munari U., Agnolin P., Tomasella L., 2001, Baltic Astronomy, 10, 613

- Munari U., Zwitter T., Katz D., Cropper M., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy, Science and Technology. Astron. Soc. Pac., Monte-Rosa, p275
- Pavlenko Y. V., Marrese P. M., Munari U., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy, Science and Technology. Astron. Soc. Pac., Monte-Rosa, p451

Pernechele C., Munari U., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy, Science and Technology. Astron. Soc. Pac., Monte-Rosa, p93

Perryman M. A. C., 1995, in Høg E., Kenneth P., eds, Proc. IAU Symp. 166, Astronomical and Astrophysical Objectives of Sub-Milliarcsecond Optical Astrometry. Kluwer Academic Publishers, the Hague, p211

Perryman M. A. C., de Boer K. S., Gilmore G., Høg E., Lattanzi M. G., Lindegren L., Luri X., Mignard F. et al., 2001, A&A, 369, 339

Piskunov N. E., 1992, in Glagolevskij Y. V., Romanyuk I. I., eds, Stellar Magnetism. Nizhnij Arkhyz, p92

Piskunov N. E., Kupka F., Ryabchikova T. A., Weiss W. W., Jeffery C. S., 1995, A&AS, 112, 525

Pourbaix D., Jancart S., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy, Science and Technology. Astron. Soc. Pac., Monte-Rosa, p345

Reininger F. M., 1994, in Cerutti-Maori M. G., Roussel P., eds, Proc. SPIE Vol. 2209, Space Optics 1994: Earth Observation and Astronomy. p332

Ryabchikova T., Piskunov N., Stempels H., Kupka F., Weiss W., 1999, Proc. 6th International Colloquium on Atomic Spectra and Oscillator Strengths. Victoria BC, Physica Scripta, Vol. 83, p162

Serote Roos M., Boisson C., Joly M., 1996, A&AS, 117, 93
Snow T. P., Welty D. E., Thorburn J., Hobbs L. M., McCall B. J., Sonnentrucker P., York D. G., 2002, ApJ, 573, 670
Sordo R., Munari U., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy, Science and Technology. Astron. Soc. Pac., Monte-Rosa, p221

Soubiran C., 2001, RVS-CS-001, ESA report

Thevenin F., Foy R., 1983, A&A, 122, 261

Thevenin F., Jasniewicz G., 1992, A&A, 266, 85

Thevenin F., Bijaoui A., Katz D., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy, Science and Technology. Astron. Soc. Pac., Monte-Rosa, p291

Torra J., Chen B., Figueras F., Jordi C., Luri X., 1999, Baltic Astronomy, 8, 171

Valdes F., Gupta R., Rose J.A., Singh H.P., Bell D.J., 2004, ApJS, 152, 251

Wilkinson M. I., Vallenari A., Turon C., et al., 2004, MN-RAS, submitted

Zwitter T., 2002, A&A, 386, 748

Zwitter T., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy, Science and Technology. Astron. Soc. Pac., Monte-Rosa, p493

Zwitter T., Castelli F., Munari U., 2003, in Munari U., ed., ASP Conf. Ser. Vol. 298, GAIA Spectroscopy, Science and Technology. Astron. Soc. Pac., Monte-Rosa, p215

Zwitter T., Castelli F., Munari U., 2004, A&A, 417, 1055