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Spectroscopic survey of the Galaxy with *Gaia* – II. The expected science yield from the Radial Velocity Spectrometer

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ABSTRACT

The *Gaia* mission is designed as a Galaxy explorer, and will measure simultaneously, in a survey mode, the five or six phase-space parameters of all stars brighter than 20th magnitude, as well as providing a description of their astrophysical characteristics. These measurements are obtained by combining an astrometric instrument with micro-arcsecond capabilities, a photometric system giving the magnitudes and colours in 15 bands and a medium-resolution spectrograph named the Radial Velocity Spectrometer (RVS). The latter instrument will produce spectra in the 848- to 874-nm wavelength range, with a resolving power $R = 11\,500$, from which radial velocities, rotational velocities, atmospheric parameters and abundances can be derived. A companion paper has presented the characteristics of the RVS and its performance. The present paper details the outstanding scientific impact of this important part of the *Gaia* satellite on some key open questions in present-day astrophysics. The unbiased and simultaneous acquisition of multi-epoch radial velocities and individual abundances of key elements in parallel with the astrometric parameters is essential for the determination of the dynamical state and formation history of our Galaxy. Moreover, for stars brighter than $V \simeq 15$, the resolving power of the RVS will give information about most of the effects that influence the position of a star in the Hertzsprung–Russell diagram, placing unprecedented constraints on the age, internal structure and evolution of stars of all types. Finally, the RVS multi-epoch observations are ideally suited

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to the identification, classification and characterization of the many types of double, multiple and variable stars.

Key words: binaries: spectroscopic – stars: general – Galaxy: evolution – Galaxy: formation – Galaxy: kinematics and dynamics – Galaxy: structure.

1 INTRODUCTION

The *Gaia* mission was approved as one of the next cornerstones of the European Space Agency (ESA) scientific programme in 2000 September, and was confirmed as one of the flagship missions of ESA Cosmic Vision in 2003 November. The mission was conceived (Lindegren & Perryman 1996) in the light of the success of *Hipparcos*, the first space astrometry mission, also operated by ESA. This first mission proved the very high potential of such an instrument by providing, for the first time, a large data set of high-accuracy, homogeneous absolute trigonometric parallaxes and proper motions. Milli-arcsecond-level accuracy was obtained for 118 000 preselected stars. More than 3000 papers using this unique set of data have been published to date, in domains ranging from reference frames to the cosmic distance scale, through stellar physics and Galactic astronomy.

Three aspects of the *Gaia* mission represent major improvements with respect to *Hipparcos*: an unprecedented astrometric accuracy of a few micro-arcseconds, the systematic, and hence unbiased, observation of some one billion objects down to a G magnitude[1] of 20, and the simultaneous acquisition of astrometric parameters and of multi-epoch, multi-colour photometry and spectroscopic observations. The overall science case for *Gaia* is impressive and multifaceted (see Perryman et al. 2001; Bienaymé & Turon 2002, and references therein). It will clarify the origin and formation history of our Galaxy through the provision of a quantitative stellar census, a kinematical and a dynamical description of each of the Galactic stellar populations, the identification of accretion debris, a determination of the Galactic rotation curve and the distribution of dark matter. It will also detect and characterize all types of stars, even the rarest types or the more rapid evolutionary phases, placing unprecedented constraints on the internal physics of stars, stellar evolution and stellar ages. The *Gaia* results will also firmly establish the distance scales in our Galaxy and far beyond, and will detect tens of thousands of double and multiple systems, variable stars, minor bodies in the Solar system, quasars and supernovae. Thousands of extra-solar planets will be systematically identified and their precise orbits and masses determined. Finally, *Gaia* will perform a strong test of general relativity by measuring the parametrized post-Newtonian (PPN) parameters γ and β with unrivalled precision.

The *Gaia* spectroscopic instrument, the Radial Velocity Spectrometer (RVS), will contribute significantly to this science case (see Munari 2003b, and references therein) by providing spectra for 100 to 250 million stars up to magnitude $V = 17$. Its key contributions will be the following.

(i) The simultaneous acquisition of the third component of the space velocity, the radial velocity, essential for kinematic and dynamical studies in the Galaxy. These data will give direct insight into the past accretion events which led to the formation of the Galaxy as it is now observed, and will place strong observational constraints on formation scenarios for the various components of the Galaxy.

(ii) Multi-epoch measurements of radial velocities, essential for the detection, classification and complete characterization of binary systems, and key observables for the determination of the fundamental parameters of pulsating variable stars.

(iii) The determination of the 'perspective acceleration', mandatory for obtaining the expected astrometric accuracy for high-velocity stars.

(iv) The astrophysical characterization of the brightest subset of *Gaia* stars, complementary to the information provided by *Gaia* photometric observations. In particular, the overall metal abundance will be derived up to $V \approx 14$–15 and individual element abundances will be obtained up to $V \approx 12$–13. For fainter stars, photometry and astrometry will be used to estimate abundance parameters – RVS spectra will calibrate these estimates at the bright end of the luminosity function. These data will help to resolve the age–metallicity degeneracy which currently hinders interpretation of the colour–magnitude diagrams that are a fundamental input to our understanding of the chemical evolution of the Galaxy.

(v) The observation of the 862-nm diffuse interstellar band which will contribute to the construction of a three-dimensional map of Galactic interstellar reddening.

The inclusion of the RVS on board the *Gaia* satellite has critical advantages over any ground-based survey because it will obtain spectra simultaneously with the astrometric parameters and photometric indices, and for systematically the same stars. Even though much effort was put into the planning of spectroscopic observations of a large proportion of the *Hipparcos* target list (Gerbaldi et al. 1989; Mayor et al. 1989) with particular emphasis on the kinematically unbiased selection of the stars to be observed, the large number of required observations has meant that the resulting measurement programme is still incomplete and only parts of it have been published (Grenier et al. 1999a,b; Nordström et al. 2004). The absence of an unbiased radial velocity data set to complement the *Hipparcos* astrometric observations constituted a severe constraint on the value of the data set for the study of Galactic kinematics. In fact, as Binney et al. (1997) emphasized, the non-uniformity of published velocities for stars in the *Hipparcos* sample meant that (in 1997) the set of stars with full three-dimensional velocity information was kinematically biased because high proper motion objects were more likely to have measured radial velocities. This had a significant impact on the potential scientific value of this data set. In the case of *Gaia*, the measurement principles ensure the total homogeneity of the observations, with the sole exception of the approximately 10 per cent of the densest regions of the Galaxy (the cores of globular clusters and the inner Galactic bulge). After the detection of particularly interesting objects, it will clearly be fruitful to observe them with ground-based instruments providing much higher spectral resolution.

[1] The characteristics of the G filter are discussed in detail by Katz et al. (2004, hereafter Paper I). For example, a G5 V star has $G - V = -0.36$.

Table 1. Precision (1σ error) of the RVS instrument in the determination of stellar parameters. The table gives the expected accuracies for effective temperature $T_{\rm eff}$, surface gravity $\log g$, iron abundance [Fe/H] and rotational velocity $v \sin i$. For all parameters other than rotational velocity, the quoted precisions will be obtained for a G5 V star to a limiting magnitude of $V \simeq 14.0$. Limiting magnitudes for other stellar types, as well as a complete discussion of the algorithms used to calculate these accuracy estimates, will be presented elsewhere (Recio-Blanco et al., in preparation). Paper I also contains some additional discussion of these performances.

Expected stellar parameter accuracies
$\sigma(T_{\rm eff}) = 75 \pm 55$ K
$\sigma(\log g) = 0.16 \pm 0.12$ dex
$\sigma([{\rm Fe/H}]) = 0.11 \pm 0.08$ dex
$\sigma(v \sin i) = 5\,{\rm km\,s^{-1}}$ to $V = 15$ for late-type stars
$\sigma(v \sin i) = 10$–$20\,{\rm km\,s^{-1}}$ to V=10–11 for B5 main-sequence stars

Table 2. Precision (1σ error) of the RVS instrument in the determination of radial velocities. The quantity σ_1 is the 1σ error in radial velocity at the limiting magnitude V_1 after a single transit of the RVS instrument; σ_2 is the 1σ error in radial velocity at the limiting magnitude V_2 after 102 transits (= average number of transits per star during the mission); V_3 is the limiting magnitude for velocity errors of $1\,{\rm km\,s^{-1}}$ after 102 transits. Results for four stellar types are shown: an F2 II, a G5 V and a K1 III star each of solar metallicity, and a low-metallicity K1 III star. In each case, the limiting magnitudes V_1 and V_2 are taken to be the faintest magnitudes (to the nearest 0.5 mag) at which the radial velocity error is $\lesssim 20\,{\rm km\,s^{-1}}$. For more details see Paper I.

Expected radial velocity accuracies							
Type	[Fe/H]	$v \sin i$	σ_1	V_1	σ_2	V_2	V_3
F2 II	0.0	20	14.4	13.5	20.8	16.5	13.0
G5 V	0.0	5	19.7	14.5	16.0	17.0	14.0
K1 III	0.0	5	11.5	15.0	10.6	17.5	14.0
K1 III	−1.5	5	11.7	14.5	10.3	17.0	14.0

This paper summarizes the expected impact of the RVS on our knowledge of Galactic structure and evolution (Section 2); binary star statistics and characterization (Section 3); and stellar physics and evolution, as well as variable stars (Section 4). In Section 2.1 we briefly summarize the performance of the RVS in estimating velocities as a function of position on the sky, as this determines the contribution which the RVS will make to our understanding of the various components of the Galaxy. Tables 1 and 2 summarize the expected precisions and limiting magnitudes for various stellar parameters including radial velocity. For more details of the performance of the RVS instrument, the reader is directed to Paper I. In the present paper, we emphasize the most important potential scientific contributions of the RVS. However, we note that there will be other topics, in addition to those discussed here, for which the RVS data set will be valuable.

2 GALACTIC STRUCTURE AND EVOLUTION

One of the key science drivers for the *Gaia* mission is to determine the current dynamical state and formation history of the Milky Way. Radial velocities provide the sixth phase-space coordinate, vital for building a complete picture of the stellar dynamics in the Galaxy. In this regard, an unbiased sample of radial velocities is an essential complement to the *Gaia* proper motion and distance data set. The presence of the RVS on board the *Gaia* satellite will ensure that multi-epoch radial velocities will be acquired in an unbiased manner for all stars brighter than $V \sim 17$.

The most popular scenario for the formation of the Milky Way involves the merger of several similar-sized systems (the exact number of which may vary between 5 and 20) up to a redshift $z \sim$ 2–3 (Kauffmann, White & Guiderdoni 1993; Abadi et al. 2003). These systems contribute dark matter, stars and gas. The accretion of smaller systems occurs throughout the formation history of the Galaxy, but it must have been the dominant form of mass growth since $z \sim 1$, when the thin disc probably began to form. It is unclear whether the bulge of the Galaxy was formed from the mergers of equal-size objects at very high z, or from the instability of a pre-existing disc. At high z, when mergers were more frequent, it seems quite likely that discs could easily become unstable, leading to the formation of a bar/bulge. The mass accreted at later times builds up the external halo and the thin disc (Gilmore & Wyse 2001). In recent years, considerable evidence of past accretion events has been obtained (see Section 2.2). However, numerical simulations suggest that this scenario for the formation of the Galaxy is not without its problems. For example, there is an apparent discrepancy between the hundreds of smaller sub-haloes surrounding a simulated Milky Way-type galaxy in a standard Λ cold dark matter (ΛCDM) universe and the 11 dwarf satellite galaxies which are observed to orbit the Milky Way (e.g. Moore et al. 1999). Abadi et al. (2003) also raise the concern that simulated ΛCDM disc galaxies typically have significant bulge components which may be difficult to reconcile with the observed numbers of nearby, pure-disc galaxies. It is therefore important to place observational constraints on the possible formation histories of the various Galactic components. The most direct way to do this is to look for correlations between the ages, metallicities and space motions of their associated stellar populations.

In this section, we highlight some of the key Galactic stellar populations that will be amenable to study with the RVS, and the scientific issues that can be addressed using the RVS data set. We note that this is not intended to be an exhaustive review of Galactic structure or of the contribution of the *Gaia* mission as a whole to our understanding of the Galaxy, but rather a discussion of the key contributions in this area to be expected from the RVS instrument.

2.1 Expected RVS velocity performance

Fig. 1 shows the stellar number density for all stars brighter than $F = 17.5$ as a function of Galactic coordinates l and b taken from the Guide Star Catalogue II (GSCII: Bucciarelli et al. 2001). This spectral band is close to that of the RVS, and in what follows we assume that these number densities are representative of those that the RVS will encounter. As is discussed in Paper I, crowding at low Galactic latitudes severely limits the ability of the RVS to provide robust velocity measurements. Simulations of the effects of crowding (Zwitter 2003b) have demonstrated that degradation of radial velocity determinations sets in when the number density exceeds about 2×10^4 stars per square degree. In the figure, red and black correspond to stellar densities above 2×10^4 and 4×10^4 stars per square degree, respectively. Thus it is likely that the region of the sky within 10° of the Galactic Centre will not be observable with the RVS. Techniques for the extraction of radial velocities from the data in crowded fields are still being investigated, with the prospects of some (limited) improvements over what is currently achievable. We also note that the stellar densities in the figure are averaged over tiles of 1 square degree. It is well known (e.g. Popowski, Cook & Becker 2003) that extinction levels towards the Galactic Centre vary on small scales, and so regions of high stellar density may be adjacent to regions of significantly lower density. However, since the

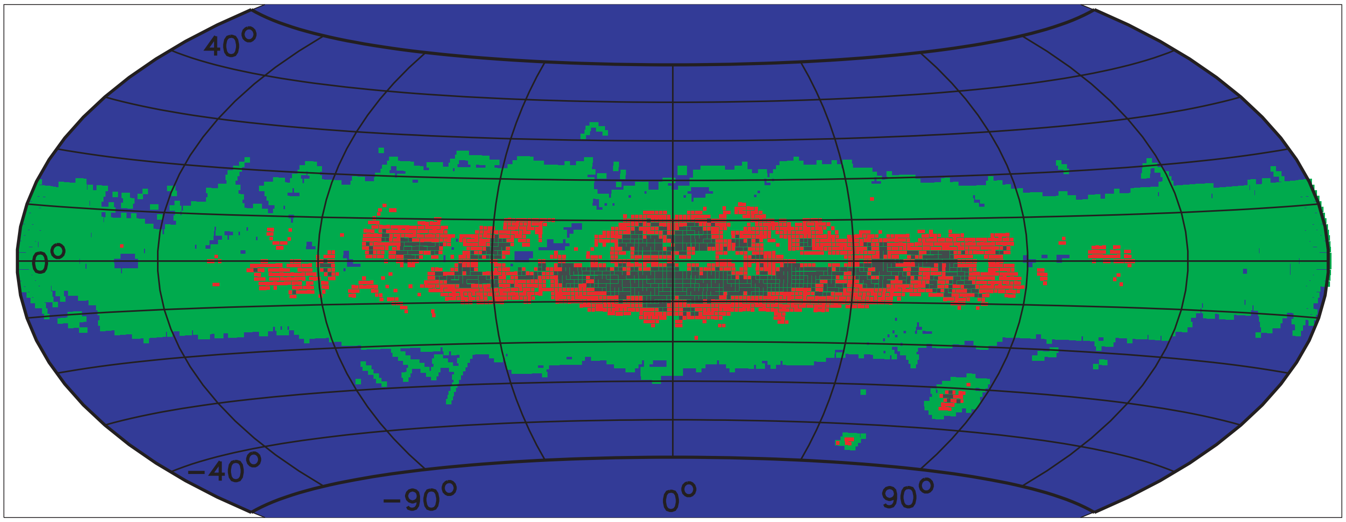

Figure 1. Stellar density as a function of Galactic coordinates (l, b) for stars brighter than $F = 17.5$ in the GSCII catalogue. Note that the typical $V - F$ colour of the disc stellar populations is about 0.6. Different colours correspond to regions in which the stellar density is (i) less than 5×10^3 deg^{-2} (blue), (ii) 5×10^3–2×10^4 deg^{-2} (green), (iii) 2–4 $\times 10^4$ deg^{-2} (red) and (iv) above 4×10^4 deg^{-2} (black). Current simulations show that the blue and green regions will be fully observable by the RVS. However, the black regions will be inaccessible, as well as some of the red regions.

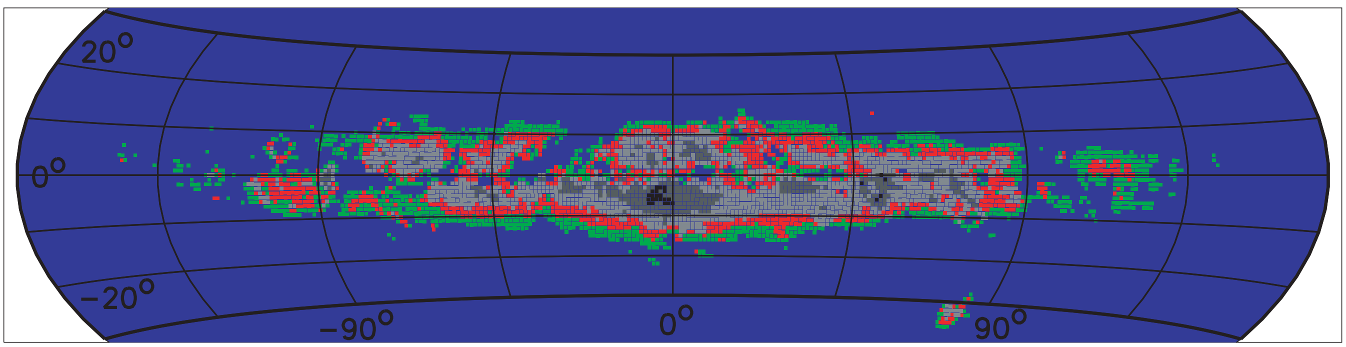

Figure 2. Expected limiting magnitude $F_{\rm lim}$ for RVS radial velocities as a function of Galactic coordinates (l, b). The colours correspond to limiting magnitudes of $F_{\rm lim} = 17.5$ (blue), $F_{\rm lim} = 17.25$ (green), $F_{\rm lim} = 16.75$ (red), $F_{\rm lim} = 16.25$ (light grey), $F_{\rm lim} = 15.25$ (dark grey) and $F_{\rm lim} = 14.25$ (black). Note that this plot does not take into account telemetry issues which will affect the densest regions of the Galaxy. See text for discussion.

lowest extinction regions (e.g. Baade's Window) have stellar densities exceeding 10^6 stars per square degree, Fig. 1 probably gives a realistic reflection of the regions in which the RVS will be able to observe.

For stars of a given apparent magnitude $F_{\rm lim}$, simulations have shown that, for late-type stars, severe degradation of the radial velocity accuracy occurs if the total stellar density of stars to a limit roughly 0.75 mag fainter than $F_{\rm lim}$ exceeds 2×10^4 stars per square degree. Thus, for a given region of the sky, it is possible to determine an effective magnitude limit above which we can expect the RVS to provide accurate radial velocities. Fig. 2 shows the effective limiting magnitude for radial velocity measurements as a function of position on the sky. This shows that over most of the sky the RVS will be able to obtain velocities to a magnitude limit of between $F_{\rm lim} =$ 16 and 17, although in the direction of the Galactic Centre this limit is significantly brighter. Given that the disc populations have a mean $V - F$ colour of 0.6, the limiting V magnitude will range between 16.85 and 17.5 over most of the sky. In fact, telemetric constraints will severely restrict the amount of data from the Galactic Centre region that can be obtained, and so the magnitude limit for these regions in Fig. 2 is probably optimistic. In the following, we assume that the RVS performances described in Paper I will be achieved over approximately 90 per cent of the sky, as suggested by Figs 2 and 1.

2.2 The stellar halo and debris streams

If the Milky Way was built via accretion as in the hierarchical formation model (e.g. White & Rees 1978), accretion events should have left fossil signatures in its present-day components, which should be clearly detectable with *Gaia* (Helmi & White 1999; Abadi et al. 2003). The most natural place to look for such substructures is the Galactic stellar halo, since a spheroidal component is formed by the trails of stars left by disrupted satellite galaxies (Johnston, Spergel & Hernquist 1995; Morrison et al. 2000). Moreover, it is here where the most metal-poor stars are found, which could imply that this component was in place very early on (Freeman & Bland-Hawthorn 2002).

Recent observations have shown that indeed considerable structure is still present in the halo of the Milky Way, indicating that accretion events have had some role in its formation history (e.g. Ibata, Gilmore & Irwin 1994; Majewski, Munn & Hawley 1996; Helmi et al. 1999; Ivezić et al. 2000). The existence of a substantial counter-rotating halo component is suggested by RR Lyrae and blue horizontal branch (BHB) star kinematics (Majewski 1992; Carney 1999). In the solar neighbourhood, it is unclear whether the local halo velocity distribution is well approximated by a smooth Gaussian (Martin & Morrison 1998; Chiba & Beers 2000) which might point to the presence of substructure. A large fraction of the substructures discovered so far are located in the outer regions of our Galaxy, where the debris can remain spatially coherent for many Gyr. This implies that it can be recovered from low-dimensionality surveys, such as 2D (using two sky coordinates), 3D (using also distance) or 4D (including radial velocities) maps. Many surveys have been able to discover debris using this approach, which requires suitable tracers such as giant stars [BHB, RR Lyrae, red giant branch (RGB)] to probe the outer Galaxy. These surveys include the Sloan Digital Sky Survey (SDSS: Yanny et al. 2000), the Spaghetti Project Survey (SPS: Morrison et al. 2000), the Quasar Equatorial Survey Team (QUEST) RR Lyrae survey (Vivas et al. 2001), the Two-Micron All-Sky Survey (2MASS: Rocha-Pinto et al. 2003) and a few smaller ones.

One of the most spectacular findings has been the discovery of debris from the Sagittarius dwarf galaxy, which spans a complete great circle on the sky (Rocha-Pinto et al. 2003). We are presently witnessing the merging of a satellite galaxy, which is just now contributing stars to build up the outer stellar halo of our Galaxy. In fact, most of the halo substructure discovered so far can be attributed to the Sgr dwarf (Ibata et al. 2001b; Martínez-Delgado et al. 2001; Dohm-Palmer et al. 2001; Newberg et al. 2002; Martínez-Delgado et al. 2004). It is unclear whether other accretion events in the outer halo still await discovery, although this should probably be the case if the Galaxy was built hierarchically. The present situation may be understood from the fact that the streams discovered so far are dynamically the youngest, and hence the easiest to detect. It is quite likely that other debris has escaped detection because of its low surface brightness. Observationally, we need to keep in mind that no surveys have yet reached both the required depth and sky coverage. An ideal survey would need to have a magnitude limit not brighter than $V = 19$ or 20, excellent photometry to allow identification and reliable distance estimation, and preferably spectroscopic follow-up to measure radial velocities to an accuracy of $10\,\mathrm{km\,s^{-1}}$, and its sky coverage should allow the tracing of tidal trails over large portions of the sky, which would require at least a few thousand square degrees.

Most of the stars in the Galactic halo are, however, inside the solar circle. Thus it is the inner halo that contains most of the information related to the merging history of our Galaxy. However, in this region of the Galaxy, the debris from a disrupted satellite galaxy phase-mixes rapidly (a simple consequence of the shorter orbital time-scales and the more flattened nature of the Galactic potential), erasing spatial correlations almost completely (Helmi & White 1999). Nevertheless, the debris still retains its coherence in phase space which is reflected in its kinematics. For example, if the whole stellar halo were built from merged satellites, we would expect between 300 and 500 (mainly) cold streams in the solar neighbourhood, the origin of which could be traced back to those satellites (Helmi & White 1999; Helmi et al. 2003a).

To test this prediction, large samples of halo stars with accurate 3D velocities are required. For example, to resolve the stellar halo velocity ellipsoid near the Sun into the individual streams at a 3σ level implies that the required accuracy in any velocity component $\epsilon_{\rm v}$ should satisfy

$$\epsilon_{\rm v}^n = \frac{\sigma_{\rm halo}^n}{3^n N_{\rm streams}}. \qquad (1)$$

Here $\sigma_{\rm halo}$ is the typical velocity dispersion of halo stars near the Sun and is approximately $100\,\mathrm{km\,s^{-1}}$, $N_{\rm streams}$ is the number of streams predicted in a small volume around the Sun, which is of the order of 500, and n is the dimensionality of the kinematic survey. Thus, if radial velocities alone are available, then the required accuracy is $\epsilon_{\rm v} \lesssim 0.07\,\mathrm{km\,s^{-1}}$. If only the tangential velocities are available, then $\epsilon_{\rm v} \lesssim 1.5\,\mathrm{km\,s^{-1}}$, while, in the case where all three components are obtainable, $\epsilon_{\rm v} \lesssim 4.2\,\mathrm{km\,s^{-1}}$, which is within the reach of the RVS (for a K1 III star, this precision will be achievable for stars brighter than $V = 16.0$–16.5 depending on metallicity). Clearly, knowledge of the radial velocities is critical for the discovery of streams and the measurement of their properties. It is worth emphasizing that kinematically cold streams are expected even in the full hierarchical regime, where mergers of systems of more equal mass, rather than simple satellite accretion, are dominant (Helmi, White & Springel 2003b).[2] The clumpiness in the kinematics of halo stars should thus be a distinct feature of the hierarchical formation of our Galaxy.

Since an individual disrupted satellite may give rise to many streams in a small volume around the Sun [for example, an object of the size of the Small Magellanic Cloud could produce about 30 streams after orbiting the inner Galaxy for a Hubble time (see Helmi & White 1999)], more sophisticated methods are needed to identify the debris observationally. Helmi & de Zeeuw (2000) proposed a method based on the expected clumpiness in the space of the integrals of motion (energy, angular momentum) for stars having a common origin. This method has been successfully applied to the solar neighbourhood to identify an ancient minor merger that contributed 10 per cent of the nearby halo stars (Helmi et al. 1999).

Helmi & de Zeeuw (2000) simulated the entire stellar halo of the Galaxy starting from disrupted satellite galaxies,[3] and 'observed' it with the *Gaia* satellite by convolving the positions and velocities of the particles in the simulations with the expected errors. They showed that the initial clumping in the space defined by energy E, total angular momentum L and its z-component L_z is maintained to a great extent even after 12 Gyr of evolution and the error convolution. Fig. 3 presents the results of observations of the same simulations but incorporating the most recent error estimates for the observed parallaxes and the expected RVS radial velocity errors. In addition, a magnitude limit of $V = 17.5$ has been assumed [Helmi & de Zeeuw (2000) assumed a limit of $V = 15$].

Fig. 3 illustrates the importance of radial velocities in the identification of the streams in the solar neighbourhood. The top left-most panel in the figure shows the sky distribution of particles from a simulation of a disrupted satellite orbiting for 8 Gyr in the outskirts of the Galaxy with an apogalactic distance of about 60 kpc and a perigalacticon of about 20 kpc. The particles correspond to red giant stars (each assumed to have an absolute magnitude of $M_V = +1$) located within 40 kpc of the Sun (after error convolution). The region highlighted in blue contains only those stars that are within 10 kpc of the Sun. The panel beneath shows their motions (v_α, v_δ) as would be derived only on the basis of their proper motions and

[2] This is a consequence of the conservation of phase-space density: as tidal debris spreads out in coordinate (physical) space, the local velocity dispersion decreases, so cold streams are expected if the mergers took place a relatively long time ago.

[3] Their simulations of satellite disruption adopted a fixed Galactic potential, and hence are quite idealistic and may not be very representative of the conditions found in a hierarchical universe. However, Knebe et al. (2005) used CDM simulations with a live Galactic potential and found that substructures do remain quite coherent in energy–angular momentum space.

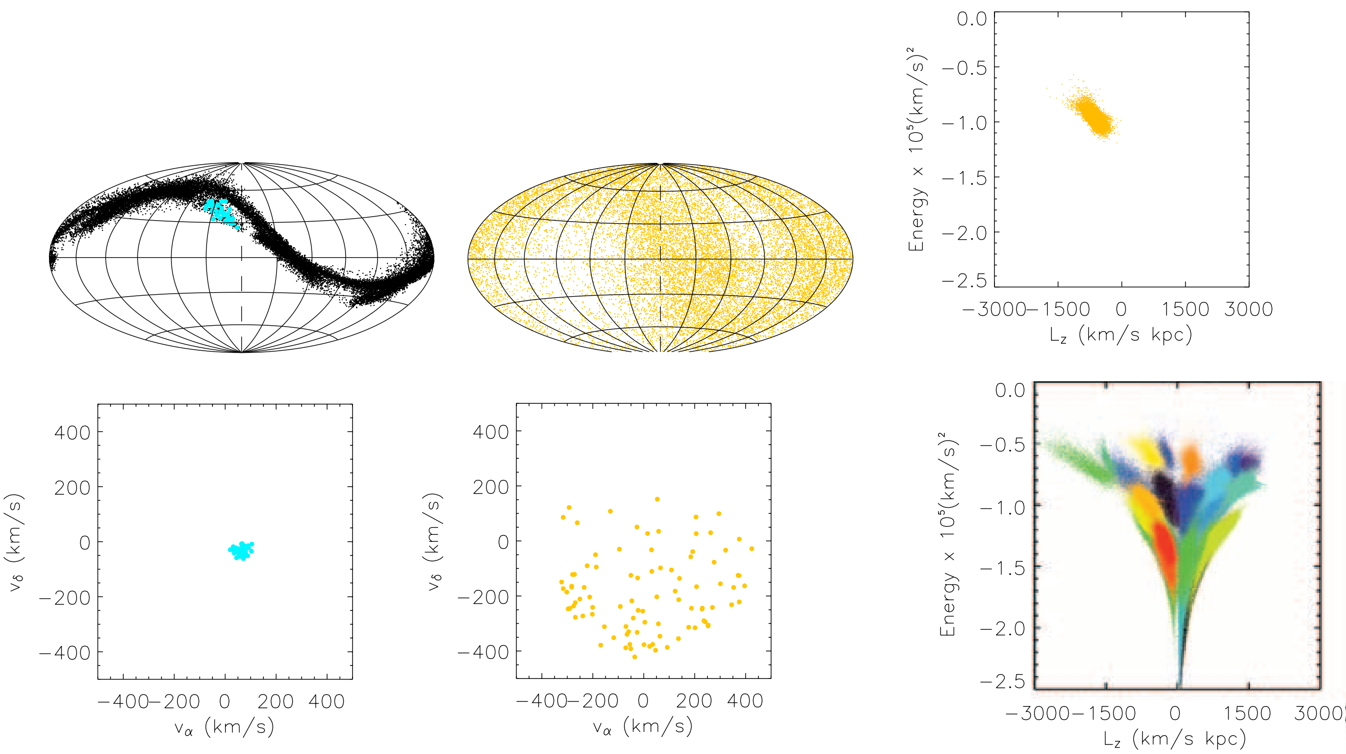

Figure 3. Distributions, in real space and velocity space, of stars resulting from the accretion of a satellite galaxy by the Milky Way, illustrating the importance of radial velocities in the identification of stellar streams in the inner halo. Left: results for a stream in the outer halo (top panel: real space; bottom panel: velocity space) – the blue points represent stars within 10 kpc of the Sun. Middle: results for a stream in the inner halo (top panel: real space; bottom panel: velocity space). Right: distribution of integrals of motion for the inner halo satellite at the end of the simulation (top panel), and distribution of integrals of motion for stars originating in 33 individual satellites which could contribute to the stellar distribution of the inner halo (bottom panel). The data in each panel are convolved with expected *Gaia* observational errors in all quantities. See text for a detailed discussion.

parallaxes. It is clear that the astrometric information alone is useful for finding debris in the outer halo.

The middle panels in Fig. 3 illustrate the case of a stream in the inner halo. The top panel shows the sky distribution of particles from a simulation of a satellite orbiting in the inner Galaxy with an apogalacticon of about 12 kpc and a perigalacticon of about 4 kpc. The bottom panel shows the (v_α, v_δ) distribution of the stars located in a sphere of 1.5 kpc radius around the Sun and for which the velocity errors are less than 25 km s^{-1} and relative distance errors less than 30 per cent. Clearly, astrometric information alone is not sufficient to find debris streams in the inner halo.

Given that most of the stellar halo mass is actually located in the inner halo, it is vital that we are able to identify stellar streams in this volume also. The top right-hand panel of Fig. 3 shows the distribution of energy E and angular momentum about the z-axis L_z for all the stars from the inner halo satellite after error convolution. As Helmi & de Zeeuw (2000) found, the stars retain their clustering in the space defined by the integrals of motion. For each star in the RVS sample, both E and L_z can be computed. The bottom right-hand panel shows the (L_z, E) distribution for stars originating in 33 different satellites that could be populating the present-day stellar halo. For each star, E and L_z have been computed after proper error convolution on all observed quantities. A standard friends-of-friends algorithm applied to the (L_z, L, E) space (where L is the magnitude of the total angular momentum vector) is able to recover two-thirds of all the satellites. The use of 6D information is critical for the recovery of these accretion events: this would not be possible without the radial velocity information provided by the RVS.

More realistic, cosmologically motivated, models of the Galaxy and in particular of its stellar halo, as well as a deeper understanding of the phase-space structure of the debris from mergers, need to be produced. These would enable us to develop more refined methods to recover the debris observationally and, once the *Gaia* data are available, to unravel the formation history of our Galaxy.

2.3 Dark matter in the Milky Way

Our knowledge of the total mass and extent of the dark halo of the Milky Way is sadly lacking given its importance for comparisons with theories of galaxy formation (e.g. Kochanek 1996; Wilkinson & Evans 1999). The RVS will significantly enhance our understanding of the dark matter distribution within 50 kpc of the Galactic Centre.

The volume and column mass density of the Galactic disc place limits on the nature of the dark matter which makes up the halo. Locally, we can place robust limits on the mass in stars and gas based on star counts and our knowledge of the stellar mass function. The total mass implied by models of the stellar kinematics can be compared with the observed mass (e.g. Kuijken & Gilmore 1989; Crézé et al. 1998; Chen et al. 2003). Current estimates suggest that the two approaches yield similar values, which argues against the presence of a significant amount of dark matter in the Galactic plane and therefore the existence of dissipational forms of dark matter. The scaleheight of any unseen component can be inferred from observations of populations at a range of radii and heights above the Galactic plane which will show the variation of volume density within the disc. As Kuijken & Gilmore (1989) discuss, a key uncertainty in current estimates of the local mass density lies in the uncertain variation in the 'tilt' of the stellar velocity ellipsoid as a function of height or, in other words, whether the velocity ellipsoid is aligned with the axes of a spherical (maximal tilt) or cylindrical (no tilt) coordinate frame. The accuracy of the RVS velocities will be sufficient to map out the velocity structure over a large volume surrounding the Sun. For example, the radial velocities of metal-poor K1 III stars will be measurable with accuracies of $<5\,\mathrm{km\,s^{-1}}$ to a limiting magnitude of $V \simeq 16$, corresponding to a distance of 10 kpc (assuming $M_V = 1$). Radial velocities are necessary to determine the detailed shape of the velocity distribution in a model-independent way.

Another important quantity related to the mass of the Milky Way is the local escape speed v_e. An estimate of v_e may be obtained by studying the high-velocity tail of the stellar velocity distribution in the solar neighbourhood (e.g. Leonard & Tremaine 1990; Kochanek 1996; Meillon 1999). Current samples include only a few tens of high-velocity stars (Carney et al. 1994; Meillon 1999; Sakamoto, Chiba & Beers 2003) which only weakly constrain the shape of the velocity distribution. Radial velocities are necessary for this work as any underestimate of the space velocities of the stars translates directly into an underestimate of the escape velocity. Further, given that the estimate of v_e currently requires assumptions to be made about the shape of the velocity distribution of weakly bound stars, large samples of high-velocity stars with accurate proper motions and radial velocities are essential to specify the shape without recourse to models. The accuracies required are not particularly demanding as the typical high-velocity stars are moving at velocities in excess of $350\,\mathrm{km\,s^{-1}}$. BHB stars belonging to the stellar halo are a valuable tracer population for this work as they are numerous and relatively bright ($M_V \sim 0.6$). For a typical metal-poor, halo BHB star, the RVS will be able to obtain velocities to a limiting magnitude of about 16.5, corresponding to distances of about 15 kpc. There will be about 10 000 such stars in the observable volume, which will place strong constraints on the actual shape of the local halo velocity distribution.

The question of the full extent and mass of the Milky Way halo remains an open issue. Recent estimates (e.g. Kochanek 1996; Wilkinson & Evans 1999) which include all available data on tracer objects outside 20 kpc still have uncomfortably large error bars. A radial velocity accuracy of 10–15 $\mathrm{km\,s^{-1}}$ is sufficient for this work. Stars at the tip of the RGB will be observable to distances of about 50 kpc, while asymptotic giant branch (AGB) stars ($M_V \sim -2.5$) will be observable out to about 60 kpc. Samples of several hundred of each of these tracers will be observed by the RVS out to the orbit of the Large Magellanic Cloud. In addition, CH-type carbon stars with $M_V \sim -2.5$ will be observable out to 60 kpc. The density of these stars on the sky is about four times higher than that of AGB stars (Totten & Irwin 1998) and so a sample of about 1000 objects is expected.

Simulations show that a sample of 500 tracers extending to large radii can reduce the error on the estimate of the enclosed mass to about 20 per cent and remove systematic errors (see fig. 12 of Wilkinson & Evans 1999). The RVS will provide such a sample extending to about 50 kpc. More importantly, it will also be possible to look for correlations in the motions of the tracers which would provide information about the origins of the stellar halo. Recent observations of stars in the outer halo suggest that a significant fraction of this Galactic component may be composed of streams (Majewski 2004). Knowledge of such correlated motions is important for estimating the mass of the Galaxy, as mass estimators generally assume that all tracers are drawn independently from an underlying velocity distribution. The unambiguous characterization of a stream requires all three components of the stellar velocity – radial velocities alone place much weaker constraints, except for stars near the turning points of an orbit (e.g. Clewley et al. 2005). *Gaia* parallaxes will not provide accurate distances for these distant halo tracers. However, the *Gaia*-calibrated distribution of absolute magnitudes for particular tracers, including any dependence of absolute magnitude on metallicity or other internal parameters, will make it possible to obtain reliable photometric distances. If we conservatively assume that these distances can be calculated with an accuracy of about 10 per cent, transverse velocities for all the above halo tracers can be obtained with uncertainties of about 10–15 km $\mathrm{s^{-1}}$. Thus we can expect to have full space motions for samples of several thousand stellar tracers out to 50–60 kpc. Obtaining all-sky radial velocity coverage to an equivalent magnitude limit from a ground-based survey would be extremely time-consuming.

The nature of the dark matter which makes up the dark haloes of galaxies is also an open question. In addition to improving our knowledge of the distribution of mass within the Milky Way, which itself constrains the properties of the dark matter, the RVS will also provide a direct test of the lumpiness of the dark halo. Yoo, Chanamé & Gould (2004) have investigated the expected distribution of wide stellar binaries in haloes composed of massive compact objects (MACHOs), and find that encounters with MACHOs tend to disrupt the widest binaries and lead to a cut-off in the distribution of binary separations. Using the observed distribution of binary separations from a large sample of halo binaries (Chanamé & Gould 2004), Yoo et al. conclude that the dark halo cannot contain a significant fraction of its mass in the form of compact objects with masses above 43 $\mathrm{M_\odot}$. The velocities furnished by the RVS, in combination with the *Gaia* proper motions, will permit confirmation of the physical association of all the binaries that Yoo et al. consider by providing the full space motions of their components. Further, it will be possible to investigate the Galactic orbits of these binaries, which has implications for their expected survival times in a lumpy halo. In addition, a vastly larger sample of wide halo binaries will be obtained, which will make it possible to apply this test of the nature of the dark matter over an increased volume of the dark halo.

2.4 Disentangling the thin and thick disc populations

The study of the kinematics of the disc of the Milky Way is important for a number of reasons. First, the thin and thick discs are major components of the Galaxy and provide an opportunity to study the internal dynamics of a galactic disc at a level of accuracy that is impossible for external galaxies. Secondly, information about the formation processes that produced the disc can be inferred from the motions of its stars. The RVS will be an essential tool in the study of the disc as it will provide velocities of sufficient accuracy to probe all aspects of disc kinematics.

In order to investigate the formation of the Galactic thin and thick discs, it is vital to obtain precise information on the global Galactic kinematic properties (i.e. the velocity ellipsoids) so that deviations from expected behaviour can be reliably derived. At present, the kinematics of thin-disc stars are poorly known: the structure of the velocity ellipsoid, its vertex deviation and inclination with respect to the Galactic plane rest on a small sample of local stars. The vertex deviation measures the extent to which the local velocity ellipsoid is radially aligned and is strongly affected by the presence of moving groups in the local sample (see Section 2.5). Soubiran, Bienaymé & Siebert (2003) suggest vertex deviations which range from about 25° for young stars to about 0° for older stars, while Dehnen & Binney (1998) find that older stars have a vertex deviation of about 10°.

Additionally, to date, the vertical tilt parameter $\lambda(R)$ of the thin-disc velocity ellipsoid remains ill-determined. The value of λ indicates whether the velocity ellipsoids are aligned with the coordinate axes of a spherical ($\lambda = 1$) or cylindrical ($\lambda = 0$) coordinate system. In the first case, one axis of the velocity ellipsoid points towards the Galactic Centre, while in the second case two axes are aligned parallel to the Galactic plane. The value of λ is, in fact, strongly related to the coupling of the U- and W-velocities[4] and can only be properly constrained using 3D velocities. It is found to vary between 0.4 and 0.7 at the solar circle (Cudderford & Amendt 1991; Bienaymé 1999), while no information is available at more distant locations. Although the value of λ is directly related to the shape of the gravitational potential, the current range of values are consistent with a wide range of mass distributions including an exponential disc mass distribution embedded in either a spherical halo with a flat rotation curve ($\lambda = 0.7$) or a prolate halo ($\lambda < 0.5$). More precise determinations of λ, including its variation with position in the disc, are required and will be provided by *Gaia*.

In addition to the alignment of the velocity ellipsoid, the magnitudes of the components of the velocity dispersion tensor may also vary according to the age of the stellar population considered. Lewis & Freeman (1989) argue that a gradient in velocity dispersion as a function of stellar age ought to exist. The age–velocity dispersion relationship is based on samples of stars in the solar vicinity. For example, Quillen & Garnett (2001) find that the heating of the disc saturates after about 2–3 Gyr. However, recent results by Nordström et al. (2004) suggest a continued heating of the disc. The question is still under debate and larger data sets are required in order to resolve this issue.

Information about the formation processes that produced the thin and thick discs can also be gleaned from the rotational character of the discs. The presence, if any, of vertical velocity gradients in the stellar components might be considered as another relict of the formation process (Beers & Sommer-Larsen 1995; Chiba & Beers 2000; Gilmore, Wyse & Norris 2002; Freeman & Bland-Hawthorn 2002; Soubiran et al. 2003). N-body simulations have demonstrated that radial mixing (e.g. due to the presence of transient spiral arms) can wash out chemical and age gradients close to the Galactic plane on time-scales of a few Gyr (Sellwood & Binney 2002). Thus it is possible that only weak gradients will be detectable in the thin-disc population. However, the thick disc should preserve a memory of its formation process, since radial mixing is not so effective outside the Galactic plane and vertical gradients in metallicity and velocity dispersion can, in principle, trace the formation history. These gradients are currently very poorly constrained. On the one hand, velocity gradients perpendicular to the Galactic plane are excluded by Soubiran et al. (2003); on the other hand, it has been suggested that the velocity dispersion and rotational velocity both decrease far from the disc, with a velocity gradient of about 30 km s^{-1} kpc^{-1} (Chiba & Beers 2000). The RVS will make a substantial contribution to the resolution of this issue by providing velocities for a large sample of tracers covering a significant fraction of the low-density regions of the thick disc. For example, the velocities of K1 III giants (with $M_V = 1$) will be measured to an accuracy of about 25 km s^{-1} up to distances of 25 kpc from the Sun. Preliminary simulations show that *Gaia* will be able to detect the presence of a gradient in the thick-disc rotation velocity of the order of 10 km s^{-1} kpc^{-1} (Bertelli et al. 2003).

It is also likely that the disc components of our Galaxy contain debris from past minor mergers. In particular, the thick disc could be the product of the heating of an ancient thin disc by a relatively large satellite (e.g. Quinn, Hernquist & Fullagar 1993; Velazquez & White 1999; Freeman & Bland-Hawthorn 2002). Another related possibility is that the thick disc is constituted only by debris from disrupted satellites having initially low-inclination orbits (Abadi et al. 2003): simulations show that a substantial fraction of the old disc stars could have formed in external systems. Finally, a multi-component structure with tracers of both mergers and accretions has been suggested by Gilmore et al. (2002). In all cases, kinematic substructures are expected to remain in the disc and these should be detectable by the RVS, as well as in large radial velocity surveys such as the RAdial Velocity Experiment (RAVE: Steinmetz 2003), although the latter will survey a much smaller fraction of the disc than that covered by the RVS.

Perhaps the earliest example of such an old kinematic structure with thick-disc kinematics is the Arcturus group (Eggen 1971), the nature of which needs to be confirmed (Navarro, Helmi & Freeman 2004). The recent survey of Gilmore et al. (2002) probed more distant regions of the thick disc, and found other hints of substructure. However, without full phase-space coverage for stars over a large fraction of the disc, it remains difficult to make sense of the different moving groups, and to establish whether or not they have a common progenitor.

The outer disc of the Galaxy is very complicated, with observational evidence for both the warping and flaring of the stellar distribution outside the solar circle (e.g. Djorgovski & Sosin 1989; Evans et al. 1998). Kinematic studies to date present a confusing picture of the dynamics of the warp (e.g. Miyamoto, Yoshizawa & Suzuki 1988; Smart et al. 1998). The origin of the warp is also unclear, with suggested possibilities including interactions between the disc and the halo, or an infalling satellite or infalling gas [see Robin et al. (2003) for a discussion]. While stellar proper motions are most suited for studies of warp kinematics, the RVS radial velocities can detect the bulk motion associated with the warp. For example, Feitzinger & Spicker (1987) discuss the foreshortening effect of the warp on the distribution of gas velocities in the Galaxy. For a star at $\ell = 90°$ (the direction of the maximum height of the warp above the Galactic plane) moving on a circular orbit, the foreshortening effect amounts to a change in the radial velocity of the star of about 4 km s^{-1}. The line-of-sight component of the rotation about the nodal line of the warp is also comparable in magnitude (Miyamoto, Soma & Yoshizawa 1993).

Fig. 4 presents the results of a Monte Carlo simulation of about 10 000 stars from a mixture of thin-disc, thick-disc and halo populations brighter than $V = 17$ at $(l, b) = (270°, 45°)$ derived using the Padova Galaxy Model (Bertelli et al. 1995; Vallenari et al. 2003; Bertelli et al. 2003) including expected *Gaia* accuracies on proper motions, parallaxes and radial velocities.[5] The differences between the observed and true velocity are plotted. The errors increase with distance, being less than 1 km s^{-1} closer than 1 kpc, 10 km s^{-1} at 4 kpc, and 20–30 km s^{-1} at 10 kpc. This accuracy should be compared with the typical velocity dispersion of the thin disc (less than 10 km s^{-1}), the thick disc (40–70 km s^{-1}) and the halo

[4] The U-direction is defined to be positive in the direction of the Galactic Centre, while the W-direction is positive towards the North Galactic Pole.

[5] *Gaia* is expected to measure parallaxes with a precision $\sigma_\pi/\pi < 10$ per cent for a bright star having $M_V = 0$ up to distances of 10 kpc and with a precision of 1 per cent up to 2.7 kpc. Proper motions will be known with a precision of a few μas yr^{-1} for stars brighter than $V = 14$–15 and of about 30 μas yr^{-1} for stars of $V = 18$, depending on the spectral type.

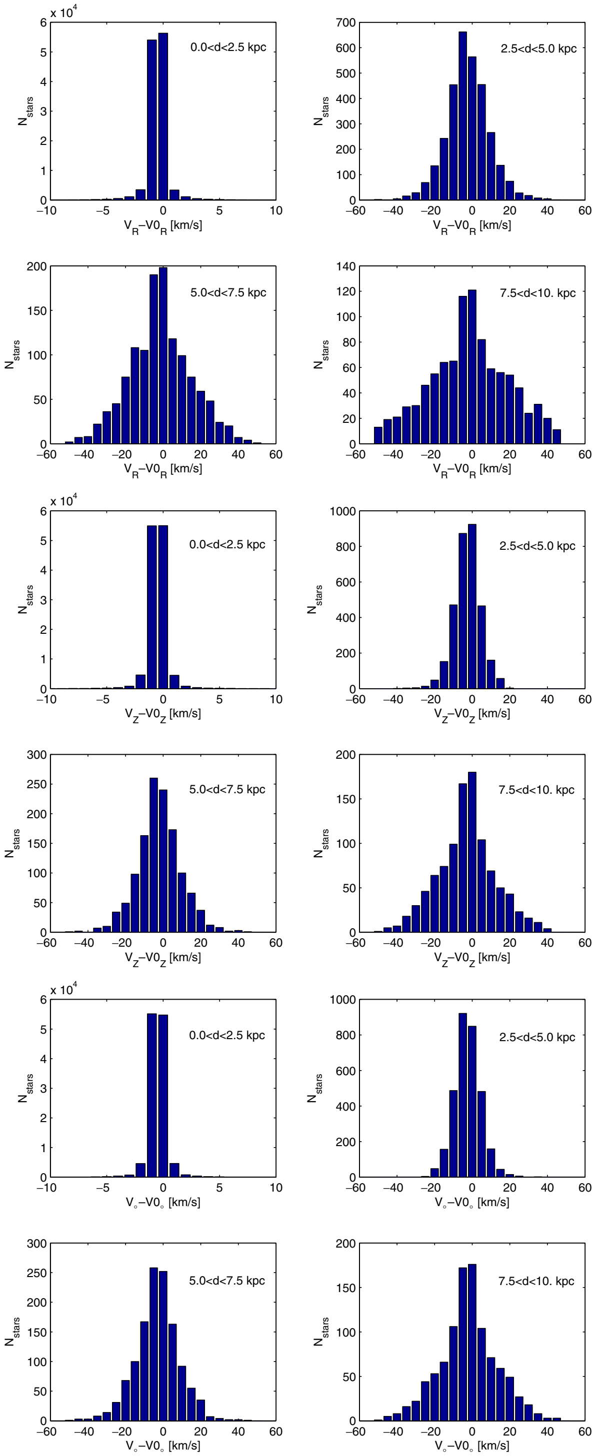

Figure 4. Distribution of velocity residuals at various line-of-sight distances in the direction $(l, b) = (270^\circ, 45^\circ)$ when *Gaia* accuracies on proper motions, radial velocities and distances are taken into account. The distributions were calculated from a Monte Carlo simulation of about 10 000 stars from a mixture of thin-disc, thick-disc and halo populations brighter than $V = 17$. The three components of the observed velocity (radial, v_R; vertical, v_z; azimuthal, v_ϕ) are shown separately.

(100–200 km s^{-1}), respectively. Thus it is clear that the velocity ellipsoids of both the thin and thick discs, as well as all other kinematic characteristics of their populations, can be derived with unprecedented accuracy.

The spiral arms associated with spiral density waves induce systematic motions of stars and gas both along and across the arms themselves and in the inter-arm regions, which can be used to map out the gravitational potential of the arm (Lin, Yuan & Shu 1969). Observations of OB associations in the Cygnus–Orion arm have shown that the magnitude of these systematic velocities is between 10 and 20 km s^{-1} (Sitnik & Mel'Nik 1999). Feitzinger & Spicker (1987) found similar velocities in their study of simulated gas velocity fields in the disc. Thus individual radial velocities with accuracies of 5 km s^{-1} are sufficient to map out the velocity field associated with a spiral arm. The RVS will be able to obtain sufficiently accurate velocities of B5 V stars to distances of about 2.5 kpc and of Cepheid tracers to distances of 6–10 kpc. These data will facilitate detailed comparisons with the spiral arms seen in numerical simulations and may provide clues to the true origin of spiral structure which is currently unclear (Sellwood 2000).

2.5 Moving groups

It is now well established that the distribution of stellar velocities in the solar neighbourhood is not smooth – well-defined groupings in velocity space are clearly visible, for example in the proper motion data from *Hipparcos* (e.g. Dehnen 1998; Famaey et al. 2005). The clumping is not random, as similar features are seen in the velocity distributions of stars of different colours. The similarity between the colour–magnitude diagrams (CMDs) derived from stars that are members of moving groups and those of open clusters led to the suggestion that these groups were the remnants of dissolved clusters the motion of which remains correlated long after the spatial coherence of the cluster has disappeared. However, the wide age range observed for stars in certain moving groups is difficult to understand in this picture, suggesting that at least some groups must have had a different origin. Recent work by De Simone, Wu & Tremaine (2004) suggests that certain old moving groups may be the product of disc heating by temporal variations in the disc potential due to the passage of stochastic spiral density waves. This would explain why stars of a variety of ages may be found in a single velocity structure. Outward-moving streams (e.g. the Hercules stream) may be the result of chaotic relaxation of stars in the non-regular parts of phase space created by the central bar (e.g. Fux 2001). In addition, the outer Lindblad resonance of the bar is near the solar radius, which may give rise to some of the observed velocity features (Dehnen 2000).

The characterization of moving groups is of great interest as it provides clues to many aspects of the internal structure of the Milky Way disc. The presence of these groups complicates the determination of the global properties of the disc populations. For example, the inclusion of a moving group in the local velocity sample can mimic the presence of vertex deviation of the velocity ellipsoid. Even the determination of the solar motion relative to the local standard of rest has been shown to depend sensitively on whether or not all the nearby moving groups are included in the stellar sample used to measure this motion (Famaey et al. 2005). As was discussed above, the complete characterization of the velocity distribution of disc stars is an essential step towards the development of a full understanding of the origin and evolution of the Milky Way disc. It will be greatly facilitated by the availability of radial velocities: the determination of the local velocity distribution using proper motions alone is equivalent to performing a difficult deprojection (Dehnen 1998). The addition of the RVS radial velocities will make it possible to determine the full (i.e. unprojected) velocity distribution function for known groups. The identification of new groups will be made more robust through the use of integrals of motion to define membership rather than merely clumping in velocity space. The velocity accuracy required is modest: individual velocity errors of about 5 km s^{-1} will suffice to distinguish between typical moving groups. As Fig. 4 shows, moving groups will be easily identified out to distances of around 2.5 kpc.

2.6 OB associations

In recent years, observations of star-forming regions have shown that stars almost never form in isolation – most, if not all, stars form in groups or clusters (e.g. Lada et al. 1991). Thus a full understanding of the details of star formation requires robust observations of young stellar clusters. The Milky Way disc contains a large number of clusters on a range of spatial scales from the low-density, unbound and expanding OB associations (e.g. Perseus OB2) to the massive open clusters (e.g. the Hyades and Pleiades clusters). The *Gaia* mission, and the RVS in particular, will improve our understanding of these objects by allowing the accurate determination of association/cluster membership based on distance and three-dimensional kinematics. The RVS will also facilitate measurements of the internal motions of stars within these systems. In addition, their collective space motions within the Galactic potential will yield insights into the connection between star clusters and the main stellar populations of the disc.

OB associations are unbound collections of recently formed stars which allow us to probe the initial mass function, primordial binary fraction and early-time dynamics resulting from the process of star formation. They are ideal locations in which to determine the fraction of stars that form in binaries as they are young stellar systems in which dynamical effects have had relatively little impact on the primordial binary population (e.g. Brown 2001b). Their internal velocity dispersions are typically a few km s^{-1}. Membership has traditionally been determined using the convergent point method (which uses only positions and proper motions but not parallaxes), although recent studies have introduced modifications to this approach (de Bruijne 1999a) as well as new techniques such as the ‘spaghetti method’ (Hoogerwerf & Aguilar 1999; Aguilar & Hoogerwerf 2001) which take account of parallax information.

It has long been known that the intrinsic expansion of OB associations resulting from gas loss cannot be determined using proper motion data alone (Blaauw 1964). In particular, it is impossible to distinguish between a radially expanding group at rest with respect to the observer and a cluster approaching along the line of sight. As Perryman et al. (1998) discuss, the standard convergent point method for the identification of members relies on assumptions (small internal velocity dispersion, no internal kinematic structure or rotation) regarding the internal motions of the cluster which can only be tested once radial velocities are available. For example, a net rotation may be inferred for a cluster with a large internal velocity dispersion if proper motions alone are used to determine membership, due to the fact that the proper motion selection will produce an artificial flattening of the cluster in velocity space. The presence or absence of rotation in star-forming regions may provide important clues to the origin of the angular momentum observed in some globular clusters (e.g. Meylan & Heggie 1997; van Leeuwen et al. 2000; Anderson & King 2003), and it is therefore important to be able to determine whether or not apparent rotation is real. The accurate determination of the orbits of young clusters and associations is of importance for the investigation of their relation to the surrounding field star population. In this context, the decomposition of any apparent radial velocity into bulk motion and expansion is clearly important. Only radial velocities, with accuracies of a few km s^{-1}, can resolve the situation.

Radial velocities are an essential complement to proper motions in the correct identification of members of OB associations, which is the first step towards their use in discussions of the issues raised above. For example, using radial velocities with errors of order 3 km s^{-1}, Steenbrugge et al. (2003) have shown that in the case of the association Perseus OB2 a number of interlopers were included in the list of possible members determined by de Zeeuw et al. (1999) based on *Hipparcos* parallaxes and proper motions alone. The inclusion of radial velocity information in the analysis provided an additional selection criterion which made it possible to identify these interlopers as unrelated field stars, due to the 10 km s^{-1} offset in radial velocity between the association and the disc stars along the line of sight. More accurate assessment of membership probabilities for stars near associations is important as it allows uncontaminated CMDs to be plotted, which in turn provide important information about the initial mass function.

Associations are often studied using only their brighter, early-type members (the OB stars). The intrinsic difficulty of obtaining radial velocities for early-type stars, particularly when only the spectral region around the Ca II triplet is available, is well known. In the case of the RVS, for a slowly rotating B5 V star ($v \sin i = 50$ km s^{-1}) with absolute magnitude $M_V = -1$, the expected velocity errors are about 2.5 km s^{-1} at 1.5 kpc ($V = 10$) and about 5 km s^{-1} at 2.5 kpc ($V = 11$), in the absence of reddening. Although radial velocities at this level of accuracy are insufficient to investigate the internal dynamics of associations (due to their small intrinsic velocity dispersions), they will be useful for the determination of association membership. In addition, spectral information allows the estimation of the extinction towards individual stars, which gives a further clue as to whether or not a given star should be associated with a particular cluster.

Associations also contain large numbers of lower mass ($M \lesssim 2\,M_\odot$) stars (e.g. Brown 2001b) for which the RVS will easily furnish radial velocities at the 1–3 km s^{-1} accuracy level. The exact numbers in particular associations will depend strongly on the local levels of extinction. However, we can estimate the range of masses that the RVS will be able to study using the properties of two known associations. The nearest OB association is Scorpius OB2, which has a distance modulus of 5.3–5.8 mag (equivalent to distances of 116–144 pc: de Zeeuw et al. 1999), solar metallicity (Eggen 1998), an age of 5–15 Myr (de Geus, de Zeeuw & Lub 1989) and visual extinction in the range $A_V = 0.1$–1.3 mag (de Bruijne 1999b). The Cepheus OB3 association is one of the most distant associations currently known, with a distance modulus of 9.65 mag (distance = 851 pc), typical extinction $A_V = 2.81$ mag, an age of less than 10 Myr and solar metallicity (Pozzo et al. 2003). We use the Padova stellar isochrones of Girardi et al. (2000) assuming solar metallicity ($Z = 0.02$) and an age of 10 Myr to determine the stellar mass corresponding to the faintest magnitude at which the RVS will obtain velocities to an accuracy of 3 km s^{-1}. For K1 III stars the magnitude limit is $V = 16$ and for F2 II stars it is $V = 14$. In the case of Scorpius OB2, we find that the RVS will be able to obtain velocities for stars with masses down to 0.4–0.7 $M_\odot$ depending on the extinction. In the more distant Cepheus OB3 this mass limit increases to about 2.2 $M_\odot$ owing to both its larger distance and higher levels of extinction. The availability of velocities for the lower mass stars in associations will allow more precise determination of the mean motion of the associations, which in turn will permit better discrimination between members and non-members of all masses.

The RVS data set will dramatically increase the sample of OB associations that can be studied in detail. There are currently about 31 known OB associations within 1.5 kpc of the Sun and which will be easily accessible to the RVS. Of these only 12 have been studied using a combination of *Hipparcos* data and ground-based radial velocities (de Zeeuw et al. 1999). In fact, six of the associations identified by de Zeeuw et al. (1999) were not included in previous catalogues, which illustrates both the difficulty of identifying associations without full kinematic information and the likelihood that the number amenable to study with the RVS will be larger than expected.

2.7 Open clusters

Somewhat more massive than OB associations, with gravitating masses sufficient to retain a bound remnant following the expulsion of the gas left over from star formation, the open clusters are important tracers of the young and intermediate-age stellar populations of the Galactic disc. Their value derives from the increased accuracy with which the distances, ages and metallicities of clusters can be determined compared with those of individual stars. Observations of a large sample of open clusters will make it possible to look for metallicity gradients in the Galactic disc which may be preserved more strongly in the open cluster distribution than in the distribution of individual stellar metallicities (e.g. Brown 2001a; Friel et al. 2002). Their internal velocity dispersions are generally a few km s^{-1}, although some (e.g. the Hyades cluster) can be less than 1 km s^{-1}. Recently, Kharchenko et al. (2005) have used an all-sky stellar catalogue to determine the observed properties of a sample of 513 open clusters (each containing at least 18 members) within about 4 pc of the Sun. The limiting magnitude in this study was $V \simeq 14$ and the authors estimate that their cluster sample is complete to a distance of about 1 kpc.

Gaia will be able to observe many open clusters – all known clusters will be amenable to study and it is expected that several thousand more will be identified within 5 kpc of the Sun. The observability of an individual cluster depends on many factors such as age, distance and extinction, all of which affect the numbers of stars with apparent magnitudes brighter than $V = 17$, and the velocity of the cluster relative to the local standard of rest, which can influence the level of contamination by foreground stars. For objects with motion lying mostly along the line of sight, stellar proper motions will be small and radial velocities will place the tightest constraints on the membership lists. Thus, as in the case of OB associations, radial velocities are essential for the construction of an accurate census of members.

For the Hyades cluster there are almost 400 stars brighter than $V = 17$ at its present location of 46.34 pc (Perryman et al. 1998). For a similar cluster at a distance of 500 pc, some 200 stars would still be observable by the RVS. At this distance the accuracy of the proper motions will be about 0.5 km s^{-1} and so the goal of achieving a comparable radial velocity error with the RVS is achievable for only a tiny minority of member stars. For these stars, however, it will be possible to trace their orbits backwards in time and hence estimate a kinematic age for the cluster by determining their epoch of smallest separation.

For nearby open clusters the RVS will provide radial velocities with errors below 1 km s^{-1} for large numbers of member stars. Even for the more distant clusters, however, the offset between the radial velocity of the cluster and the radial velocities of field stars along the line of sight means that the RVS radial velocities will generally be valuable in the construction of uncontaminated membership lists. In addition, stars that have escaped from the cluster but which remain on similar orbits within the Galaxy to that of the cluster centre of mass will be identifiable. These stars are vital to our understanding of the disruption processes that affect open clusters (e.g. de La Fuente Marcos 1996; Portegies Zwart et al. 2001). For example, de La Fuente Marcos (1996) found that in *N*-body simulations of open cluster dissolution the remnant of an open cluster which is left once the cluster has evaporated is very rich in binaries. Radial velocities will make it possible to confirm this result. The long-term evolution of clusters in the Galactic disc is also of great interest, as there is evidence that some of them, for example Cygnus OB2, are as massive as globular clusters (Knödlseder 2000). In this context, the existence of open clusters such as Berkeley 17 with ages of about 9 Gyr (Carraro et al. 1999) allows us to investigate the long-term evolution of clusters in a strong tidal field.

Young open clusters are valuable tracers of recent star formation and have been used to identify the spiral arms of the Milky Way (e.g. Feinstein 1994). Their eventual dissociation builds up the population of field stars in the Galaxy, and thus knowledge of the properties of as many such objects as possible is an important step towards understanding how the stellar populations in the Galaxy formed and subsequently evolved. As well as representing the dominant mode of current star formation in the Galactic disc, it has been suggested that the larger velocity dispersion of the thick disc compared with that of the thin disc might be partly due to the former containing a kinematically hot population of stars from clusters that became unbound by rapid gas expulsion (Kroupa 2002). The resultant characteristic mass function of young clusters constitutes an important test for this model (Kroupa & Boily 2002). A determination of the mass function of young clusters is also of fundamental importance if we want to understand the formation processes of clusters themselves – a complete census of cluster members for a large sample of young clusters is essential for this work. The cluster mass function also has implications for the chemical evolution of our Galaxy and others, because simulations have shown that long-lived, massive clusters can significantly enhance the rate of Type Ia supernovae (Shara & Hurley 2002).

The RVS will be able to test models of cluster disruption by looking for the unbound populations of stars surrounding young clusters which are the signature of the effects of gas expulsion. These stars will be easily identifiable because of the similarity of their metallicities and space motions to those of their parent cluster. In addition, the RVS will be able to detect the streams in the thick- and thin-disc populations which are expected to result from recently disrupted clusters. When a cluster becomes unbound, differential rotation and disc heating mechanisms spread the cluster stars within an elongated volume centred on the original cluster orbit. The total velocity dispersion of the stars increases with time – however, stars that are physically close together will have a lower velocity dispersion than the initial value as a consequence of Liouville's theorem (e.g. Binney & Tremaine 1987). As equation (1) shows, the velocity accuracy required to distinguish more than a few tens of streams is difficult to attain for a disc population with the dispersion of the thin disc. However, for an object that was disrupted during the past few hundred Myr there will be sufficient stars moving on orbits similar to that of the original cluster, and sharing common characteristics such as metallicity, to permit identification of the remnant.

2.8 Runaway stars

Runaway stars are isolated, early-type stars (spectral types O and B) with large peculiar velocities relative to the mean Galactic rotation.

They are thought to originate in associations, and the feasibility of tracing their orbits backwards in time in order to determine the cluster in which they formed has been demonstrated by Hoogerwerf, de Bruijne & de Zeeuw (2000) using a combination of *Hipparcos* data and radio observations. Two mechanisms that lead to the ejection of runaway stars have been suggested. One possibility is that close dynamical encounters within an association can result in stars achieving escape velocity. An alternative channel is the binary–supernova scenario in which the runaway star was originally a member of a close binary. Following the explosion of its companion as a supernova, and possibly the consequent disruption of the binary, the runaway star acquires a sufficient velocity to move out of the cluster. Both mechanisms appear to occur in nature, but their relative importance has not yet been clearly established (Hoogerwerf et al. 2000). Retracing the orbits of large numbers of runaways is essential for the identification of the dominant production channel. This will, in turn, have implications for our understanding both of the internal dynamics of associations and clusters and of the fraction of high-mass stars that form in binaries (Portegies Zwart 2000). It will also improve our knowledge of the distribution of kick velocities acquired by pulsars at formation.

Radial velocities are useful in this work for two reasons. First, knowledge of the full-space motion of the runaways makes the determination of their point of origin significantly more robust. Secondly, at present the identification of runaway stars relies on their large proper motions. The inclusion of radial velocity information will allow their identification based on a true space motion which may not lie in the plane of the sky – the RVS will therefore lead to a significant increase in the detectable sample of runaway stars.

Another interesting possibility for the post-*Gaia* modelling of the Milky Way will be to use runaway objects as tracers of the gravitational potential of the disc. An example of such an object is Cygnus X2 which Kolb et al. (2000) have suggested may have originated as an intermediate-mass X-ray binary in the Galactic disc which was subsequently driven to its present location 2.28 kpc out of the Galactic plane by the velocity kick generated in a supernova explosion. More recently, Brown et al. (2005) have identified a hyper-velocity star moving at more than $700\,\mathrm{km\,s^{-1}}$ away from the Galaxy and currently located at about 55 kpc from the Galactic Centre – its properties (including its age and metallicity) are consistent with its having been ejected from the Galactic bulge about 80 Myr ago. The *Gaia* data set will permit the identification of stars with anomalously high velocities compared with other stars in their vicinity. Determination of the orbits of a significant sample of such stars using both radial velocities and proper motions may be used to place constraints (albeit somewhat circumstantial ones) on the distribution of mass in the Galaxy.

2.9 Globular clusters

The globular clusters which orbit the Milky Way are valuable laboratories in which to study the interplay between stellar evolution and stellar dynamics. Although the central regions of many Milky Way globular clusters will not be observable using the RVS as a result of crowding, the RVS will nevertheless contribute to our understanding of these systems in a number of ways. For example, the outer regions of many clusters will be amenable to study and therefore the internal dynamics at intermediate radii can be investigated.

It is reasonable to assume that the dense regions of globular clusters will have a similar impact on the performance of the RVS to that of crowded Galactic fields of comparable surface brightness. As we discussed in Section 2.1, radial velocity estimates start to be degraded for stellar densities above 2×10^4 stars per square degree. For field stars, a limiting magnitude of $V = 17$ (i.e. a stellar density of about 2×10^4 stars per square degree brighter than $V = 17$) corresponds to an integrated surface brightness (for all stars in the magnitude range $V = 10$–20) of $V = 21.75$ mag arcsec^{-2} (see Zwitter 2003a,b). Thus stars with $V = 17$ will be observable in those regions of a globular cluster where the integrated surface brightness is fainter than 21.75 mag arcsec^{-2}.

In order to determine which Galactic clusters will be observable, we assume further that a star with $V < 17$ will be observable against a given background if the difference between the magnitude of the star and the integrated surface brightness is the same as that between a $V = 17$ star and the $V = 21.75$ mag arcsec^{-2} critical surface brightness. This implies that, for example, stars in the ranges $V = 14$–15 and 15–16 can be observed against backgrounds of $V = 19.75$ and 20.75 mag arcsec^{-2}, respectively. This assumption of a constant offset is probably conservative, since the signal-to-noise ratio of the source spectrum increases for brighter sources – it may therefore be possible to measure velocities for the brighter stars against higher background densities. From the globular cluster catalogue of Harris (1996) we extract the concentration and central surface brightness for each cluster and compute the radii within which the surface brightness is higher than the RVS limits for stars in a number of magnitude bins, assuming that the cluster can be represented by a King profile. We then calculate the proportions of the total number of stars in the cluster that lie outside these radii. Finally, using the distance, reddening, luminosity function and total mass of each cluster, we compute the number of observable stars in each bin. The cluster masses are estimated from their total luminosities using a linear interpolation between the 55 clusters for which mass estimates are available in the literature. The luminosity function of M92 is assumed for all the clusters. It is important to note that we have ignored the fact that, for some RVS transits, individual spectra may overlap denser regions of the cluster, thereby reducing the effective number of transits per star. In view of this and our other simplifying assumptions, the estimates are probably only reliable to within about a factor of 2–3. Nevertheless, they give an indication of the likely contribution of the RVS to globular cluster studies.

Fig. 5 summarizes the performance of the RVS in the Milky Way globular cluster population. In approximately 33 clusters, the RVS

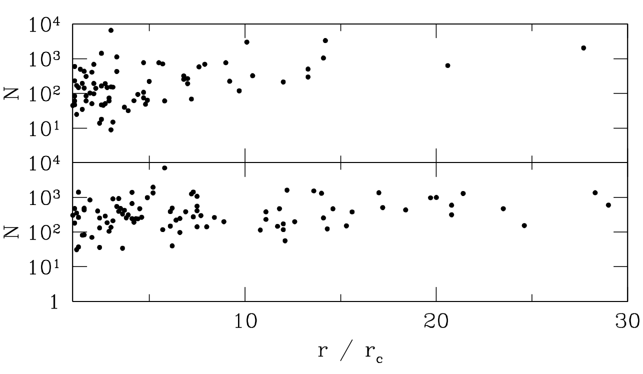

Figure 5. Performance of the RVS in Galactic globular clusters. For each cluster, the plot shows the innermost radius r (in units of the cluster core radius r_c) at which observations will be possible for stars of $V = 15$ (98 clusters: top panel) and $V = 17$ (121 clusters: bottom panel) and the total number of stars N that will be observed in the cluster with $V < 15$ (top panel) and $V = 15$ –17 (bottom panel). Clusters either that cannot be observed or in which the innermost radius is more than 30 core radii have been omitted. See text for a detailed discussion.

will be able to observe more than 100 stars brighter than $V = 15$ to within 5 core radii – for 24 clusters it will be possible to observe stars inside one core radius. The individual radial velocity errors for these stars will, in most cases, be smaller than the internal dispersion of the cluster, making them extremely useful for the discussion of the internal dynamics of the cluster. Thus the RVS will provide a large sample of stars for the detailed study of the internal kinematics of about 20–30 of the Galactic globular clusters. For 96 clusters, more than 100 stars in the range $V = 15$–17 will be observable to radii of less than 5 core radii. These latter stars will be useful for determining the bulk properties of the clusters such as rotation.

One key quantity which the RVS will constrain is the stellar binary fraction in globular clusters which, despite its importance for understanding the dynamical evolution of clusters (e.g. Hut, McMillan & Romani 1992; Wilkinson et al. 2003), is currently poorly constrained observationally (e.g Elson et al. 1998; Albrow et al. 2001; Stetson, Bruntt & Grundahl 2003). While we expect that the fraction of tight stellar binaries should decrease with increasing radius in most clusters owing to the effects of mass segregation, a limit on the binary fraction in the outer parts will at least provide a constraint on the fraction in the cluster as a whole. Cluster binaries will also be detected using the astrometric and photometric data from *Gaia*.

Accurate velocities for stars in the outer parts of clusters will permit the study of rotation in clusters as well as providing estimates for the bulk radial velocities of the clusters. In conjunction with the *Gaia* proper motions for the clusters, these will determine the orbits of all the Milky Way clusters and place tighter constraints on the mass of the dark halo (e.g. Wilkinson & Evans 1999, and Section 2.3).

The gravitational field of the Milky Way continually removes stars from the outer parts of the star clusters that orbit the Galaxy, leading to the development of tidal 'tails' of stripped stars which extend along the orbits of the clusters. There is some evidence for the presence of tails around a number of globular clusters (e.g. Leon, Meylan & Combes 2000; Odenkirchen et al. 2001). However, recent work has called into question the reality of certain of these tidal tails and, in particular, suggests that the tails of the massive globular cluster Omega Centauri are artefacts produced by differential reddening across the face of the cluster (Law et al. 2003). Kinematic studies of the outer parts of clusters are necessary in order to improve our understanding of cluster disruption by external tides.

The RVS spectra will contribute to the resolution of this issue in two ways. First, as we discuss in Section 2.11, the spectra will facilitate the construction of accurate extinction maps throughout the Galaxy. Secondly, the velocities of stars in the tidal tails of a star cluster are similar to the bulk motion of the cluster and, in general, differ significantly from those of surrounding field stars. As a result, the velocity estimates provided by the RVS (and, of course, by the *Gaia* proper motions) will often be sufficient to distinguish between escaping cluster members and field stars. Thirdly, the metallicities of cluster stars will generally differ from those of the surrounding field stars. For brighter stars, this will provide another potential confirmation of a physical connection, if any exists, between the 'tails' and the cluster.

All Galactic clusters with sufficient numbers of bright ($V < 17.5$) stars will be amenable to study via a combination of the above approaches: for example, the well-studied cluster Pal 5, the tidal tails of which have now been traced in the stellar number density distribution to distances of about 2 kpc from the cluster centre (Odenkirchen et al. 2003). While the internal velocity dispersion of the tails is too small for the RVS velocities to contribute to discussions of their internal structure [the intrinsic dispersion of Pal 5 is less than 1 km s^{-1} (Odenkirchen et al. 2002) and the spatial coherence of the streams strongly suggests that they must also be kinematically cold], the velocities will be of sufficient accuracy to distinguish tail members from Galactic field stars. This will be of particular value for those clusters with tidal tails that are are less extended or less clearly defined spatially than those of Pal 5. It is also worth noting that *Gaia* will also contribute to the identification of tidal streams by means of proper motions, since stars in tidal tails display proper motions very similar to those of cluster members and, in general, quite different from those of the field stars along the line of sight (e.g. King et al. 1998).

2.10 Chemical evolution

To build a realistic model of the chemical evolution of the Galaxy, one needs as many observational constraints as possible (Pagel 1997). These observations not only have to include the relative numbers of stars in the thin and thick disc or the halo, but also have to be able, using the stellar abundances of some chemical elements, to constrain particular model inputs, for example the rates of Type I and II supernovae. Possible by-products of these chemical abundance measurements could include the determination of an age–metallicity relation and possible gradients in the thin and thick discs (see also Section 2.13). The RVS spectra will reveal mainly [α element/Fe] ratios for late-type stars (e.g. the α elements Ca, Mg, Si and Ti), which constrain the sites of nucleosynthesis – these stars will require follow-up observations, for example, of the r-process elements not obtainable from the RVS spectra. The RVS will provide precise chemical abundances for 3–6 $\times$ 10^6 stars brighter than $V = 12$–13. This will make it possible to probe the thin/thick-disc and halo populations up to a distance of 2 kpc when K1 III stars having absolute magnitude $M_V \sim 1$ are used as tracers and up to 300 pc using G2 V stars of $M_V = 5$.

The variation of [α/Fe] among stars as a function of their location in the Galaxy will most strongly constrain models of the quantity of gas in the Galaxy at different epochs and also the supernova rate. The combination of chemical abundances and kinematical properties has revealed some difficulties with naive infall models of the Galaxy, as was first demonstrated by Nissen & Schuster (1997). It now seems difficult to support a simple infall model: this adds weight to the introduction of a more violent scenario of the formation of the Galaxy (e.g Helmi & White 1999). However, in such a scenario it is not obvious that one would expect a well-defined relation between chemical abundance ratios and age (Ryan & Smith 2003) during the epoch when Type Ia supernovae are supposed to explode ([Fe/H] ~ -1.0).

Searching for extreme Population II stars is also a challenge for the *Gaia* survey in order to determine the properties of the most metal-poor stars. These fossil stars are representative of the first phase of the Galaxy just after the hypothetical era of the Population III stars. Observing their [C/O] ratios with ground-based spectroscopy makes it possible to look for evidence of the presence of Population III stars very early on in the history of the Galaxy. Akerman et al. (2004) have discovered a possible increase of the [C/O] ratios for very metal-poor stars which would require the presence of massive Population III stars at the beginning of the formation of the Galaxy. Calcium lines will be visible even in the RVS spectra of very metal-poor stars. The Ca line at $\lambda = 854.2$ nm can be seen with an equivalent width EW = 0.0482 nm at [Ca/H] = -3 and EW = 0.0245 nm at [Ca/H] = -4 for a giant star with $T_{\rm eff} = 4800$ K, $\log g = 1.5$. This should allow the separation of a giant with [Ca/H] = -4

from a giant of [Ca/H] $= -3$ down to a signal-to-noise ratio of about 10 corresponding to $V \sim 15$ for the above types of star. Assuming that the star is a giant of absolute magnitude $M_V = 0 - 1$ then a survey for stars more metal-poor than [Ca/H] $= -3.5$ will be possible within a sphere of 5–10 kpc. *Gaia* will also be able to detect binarity among such halo stars and hence rule out mass transfer scenarios through which the carbon abundance in the primordial atmosphere of an extreme-Population II star is modified, thereby producing an incorrect diagnostic on the presence of Population III stars in the early phase (see e.g. Masseron et al. 2003).

Among the successes of the standard big bang model and of the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) experiment (Spergel et al. 2003) are the stringent constraints on predictions of primordial light element abundances. In particular, the helium abundance Y is now constrained to lie in the range 0.247–0.252. This value is then supposed to be the primordial helium content of the Galaxy. Its enrichment with time is assumed to be a consequence of multiple generations of stars and is expected to follow the enrichment of heavy elements Z. However, the details of the helium-to-metal enrichment relation $\delta Y/\delta Z$ which describes the increase in helium from primordial levels have long been debated in the literature [see Høg et al. (1998) for a review]. *Gaia* will provide a survey of several thousand binaries, many of which will have accurate age estimates, because when the masses of the components of a binary are known with accurate effective temperature, luminosity and abundance Z then the age can be determined by fitting evolutionary tracks to the two error boxes of the binary in the Hertzsprung–Russell (HR) diagram. The ages and estimates of He content deduced from these HR diagram fits can be used to discuss the helium enrichment of individual systems: for example, Lebreton, Fernandes & Lejeune (2001) present an analysis of five binaries in the Hyades cluster and determine the helium content and age of the cluster. The Galactic enrichment relation $\delta Y/\delta Z$ will be constrained not only for close binaries with solar metallicities,but also for very metal-poor binary stars.

At the same time, *Gaia* will provide the opportunity to measure magnitudes, absolute distances and chemical compositions for a substantial fraction of halo and thick-disc low-mass horizontal branch (HB) and RGB stars. These new data will supply accurate estimates of the R-parameter, i.e. the ratio between the numbers of HB and RGB stars (Iben 1968). The comparison between empirical star counts and evolutionary lifetimes provides an estimate of the helium content and in turn an upper limit on the primordial helium abundance (Zoccali et al. 2000b). Up to now the R-parameter has been estimated only in globular clusters, and current estimates are partially hampered by statistics and by the accuracy of spectroscopic measurements (Cassisi, Salaris & Irwin 2004). The new helium abundances will also provide the opportunity to estimate $\delta Y/\delta Z$ in the Galactic halo and thick disc as a function of Galactocentric distance.

2.11 Extinction maps

Interstellar absorption represents one of the major complications in the simulation of the CMDs of Galactic stellar populations along any line of sight, especially at low Galactic latitudes across the disc. The uncertainties in star count predictions caused by reddening may amount to some 26 per cent (Chen et al. 1999).

Several empirical models of Galactic absorption are available in the literature. Mendez & van Altena (1998) make use of the large-scale properties of the dust layer in the Galaxy to derive the absorption in the Galactic plane. Schlegel, Finkbeiner & Davis (1998) use the *COBE*/DIRBE 100- and 240-μm data to construct maps of the dust temperature in the Galaxy. In high-latitude regions, the dust map correlates well with maps of H I emission, but deviations are found in parts of the sky and are especially conspicuous in regions of saturated H I emission towards denser clouds and in areas of H_2 formation in molecular clouds. Recently, Drimmel & Spergel (2001) and Drimmel, Cabrera-Lavers & López-Corredoira (2003) presented a three-dimensional model of the dust distribution based on *COBE*/DIRBE infrared data. As stated by Drimmel et al. (2003), regions having anomalous emission due to warm dust are not well described by the model.

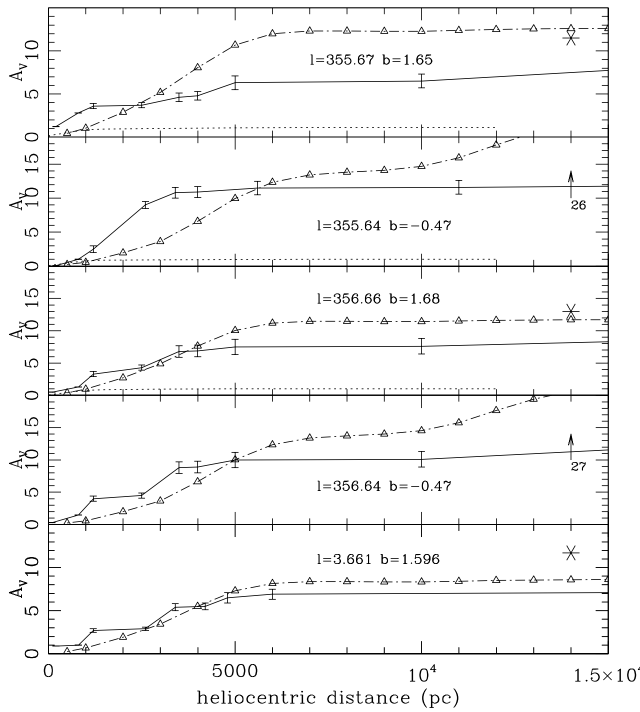

Figure 6. Extinction along several lines of sight towards the Galactic Centre. The Vallenari et al. (2003) determination (solid line in each panel) is the mean value in a field of 0°.5 × 0°.5. The error bars indicate variable reddening inside the field. The dotted line represents the model of Mendez & van Altena (1998); the dot–dashed line with triangles is the Drimmel & Spergel (2001) model including a rescaling factor. The star gives the value from the Schlegel et al. (1998) maps. When the determination from the Schlegel et al. maps lies outside the plotted range, a labelled arrow indicates the reddening value.

When comparing the various literature models of extinction in analyses of CMDs observed along the line of sight, very large discrepancies soon become apparent. First, there are still problems with the accuracy of the zero-point calibration of the extinction maps. In fact, as Burstein (2003) points out, even at high Galactic latitudes the reddening map by Burstein & Heiles (1978) provides reddening values that are 0.02 mag smaller than the reddening map by Schlegel et al. (1998). At low Galactic latitudes and towards the spiral arms, the difference may be as large as 4–5 mag (see Fig. 6 and Vallenari et al. 2003). This is due in part to variations of the dust properties on small scales and in part to the many uncertainties that are still associated with dust emission models.

The RVS can directly measure an interstellar or circumstellar extinction corresponding to $E(B-V) = 0.10$ using the 862-nm diffuse interstellar band (DIB: see Paper I) of early-type stars brighter than $V \sim 12$–13 which has been shown to be directly associated with the dust phase of the interstellar medium. Simulated RVS

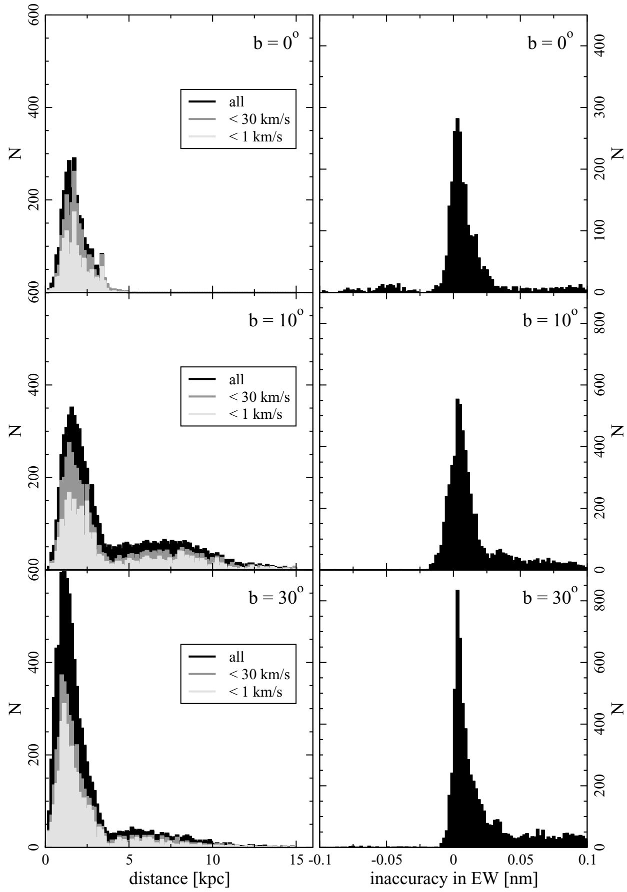

Figure 7. Recovery of the 862-nm DIB from simulated RVS spectra. The stellar spectra are obtained from the stellar population synthesis Galactic model of Robin et al. (2003). The three-dimensional model of the dust distribution of Drimmel & Spergel (2001) is used. Left: number of simulated stars as a function of distance in three Galactic directions ($l = 10^\circ$; $b = 0^\circ$, 10° and 30°). Black represents all simulated stars, dark grey those for which the DIB line was recovered with an accuracy of at least 30 km s^{-1}, and light grey those for which the recovery of the DIB line was more accurate than 1 km s^{-1}. As expected, extinction is a strong limiting factor only within the Galactic plane. Right: number of simulated stars as a function of inaccuracy in equivalent width EW, i.e. the difference between the simulated and recovered EW of the DIB line. According to Munari (2000), EW is proportional to the extinction $E(B - V)$ [an EW of 0.05 nm corresponds to an extinction $E(B - V) = 1.35$].

data indicate (see Fig. 7) that the imprint of the 862-nm DIB will be detected even in the spectra of much fainter stars with magnitudes up to $V \sim 16$ with sufficient accuracy to trace not only the distribution of the interstellar medium but also the radial component of its kinematic motion (the Doppler velocity of the mass centre of the dust cloud is calculated from the wavelength position of the DIB line centre). The resulting three-dimensional maps of interstellar extinction are independent of the photometric approach to reddening determination which is based on a comparison between observed colours and modelled intrinsic colours. Thus, the RVS will make a vital contribution to the construction of a new generation of accurate star count maps of the Galaxy which are essential to the development of complete models of Galactic structure. In addition, accurate extinction-corrected stellar magnitudes will be of enormous importance for the testing of stellar models (see Section 4), solving the degeneracy between reddening and temperature that usually affects determinations from photometry.

As an illustration of the effects of reddening on the stellar distribution in different regions of the Galactic spheroid, we selected a few well-observed fields. In particular, we focused our attention on three standard stellar fields for which Stetson (2000: see also http://cadcwww.hia.nrc.ca/standards/) collected new and homogeneous multi-band photometric data. Table 3 lists the coordinates and positional parameters of the selected fields.

Fig. 8 shows the ($V - I$, I) CMDs of the selected fields which are assumed to be representative of the number densities and extinctions for intermediate-latitude Galactic fields. The data plotted in this figure clearly show the effects of reddening. When moving from bottom to top, the reddening increases from $E(B - V) =$ 0.04 to 0.16; the increase, as expected, causes a systematic shift towards fainter magnitudes and redder colours for the field stars. This means that observed luminosity functions and colour distributions are strongly affected by the interstellar extinction and by differential extinction, if any, along the line of sight. We note in passing the large difference in the mean interstellar extinction between the Burstein & Heiles (1982) and the Schlegel et al. (1998) reddening maps (see column 7 in Table 3). This emphasizes again the crucial role of individual reddening measurements in the improvement of the accuracy of stellar parameters.

2.12 Star formation history

The determination of the history of star formation from the CMDs of composite stellar populations is an important goal of modern astrophysics. The problem is easier to tackle in galaxies in which individual stars are resolved and CMDs are derived, because we may assume that all the stars lie at almost the same distance. However, in our own Galaxy the problem is significantly more complicated because there are differences in the distances of the stars and therefore only CMDs containing stars of inhomogeneous age, chemical composition and distance are directly exploitable. Additionally, the age–metallicity degeneracy further complicates the problem. Following the *Hipparcos* mission, it was possible for the first time to derive the CMD, in absolute magnitudes, of field stars in the solar vicinity (Perryman et al. 1995) and from this CMD to study the history of the solar neighbourhood.

The *Gaia* mission will significantly exceed the performances of *Hipparcos*, permitting the determination of the star formation histories (SFHs) of the disc and halo of the Milky Way. Recently, Bertelli & Nasi (2001) determined the SFH of the solar vicinity from *Hipparcos* data, covering the total lifetime of the disc (10 Gyr). They find that from the *Hipparcos* catalogue it is possible to select a complete sample of stars with well-measured parallaxes down to $M_V =$ 4.5 in order to include main-sequence and evolved stars, inside a sphere of radius $r = 50$ pc. *Gaia* will be able to observe a much larger sample of stars, covering in distance and position a large portion of the Galaxy and possessing the same degree of accuracy as that obtained by *Hipparcos*. Bertelli (2002) has demonstrated that *Gaia* will indeed allow the study of a sample of stars complete down to $M_V = 4.5$ with a parallax accuracy better than $\sigma_\pi/\pi \leqslant$ 0.1 up to a distance of 2–3 kpc. Here it is worth remembering that, because of the effects of radial mixing in the disc in response to spiral wave perturbations, old stars born at the location of the Sun may now be spread over a range of Galactocentric radii from 4 to 12 kpc (Sellwood & Binney 2002). Within this volume, the RVS will provide information about the average metal content of the stars brighter than about $V = 14$–15 (see Table 1 and Paper I), solving the age–metallicity degeneracy which always hampers the estimation of the star formation rate from HR diagrams, in particular for older

Table 3. Parameters of selected Galactic fields which illustrate the range of conditions that the RVS will encounter at intermediate latitudes. The table presents the field name, the field of view for each observed field in square arcmin, the positions of the field centres in ecliptic and Galactic coordinates, the interstellar extinctions A_B estimated over an area of 5×5 arcmin^2 centred on the individual fields, and the estimated number of stars in each field N_s which will be detectable by the RVS. Note: two values of A_B (and the associated N_s estimates) are quoted for each field. The A_B values are taken from the Burstein & Heiles (1982) and Schlegel et al. (1998) reddening maps, respectively.

Field	Field of view (arcmin^2)	RA(J2000)	Dec.(J2000)	l	b	A_B	N_s
L95	46.0 × 50.9	$03^h54^m12\overset{s}{.}40$	$+00°13'09\overset{''}{.}0$	$188\overset{\circ}{.}79146$	$-38\overset{\circ}{.}25715$	0.67/1.51	870/1090
L107	44.1 × 37.5	$15^h39^m20\overset{s}{.}90$	$-00°20'25\overset{''}{.}9$	$5\overset{\circ}{.}70550$	$41\overset{\circ}{.}22154$	0.29/0.48	1170/1525
MarkA	33.9 × 26.9	$20^h43^m43\overset{s}{.}20$	$-10°46'16\overset{''}{.}9$	$35\overset{\circ}{.}89721$	$-29\overset{\circ}{.}77091$	0.18/0.25	1700/2215

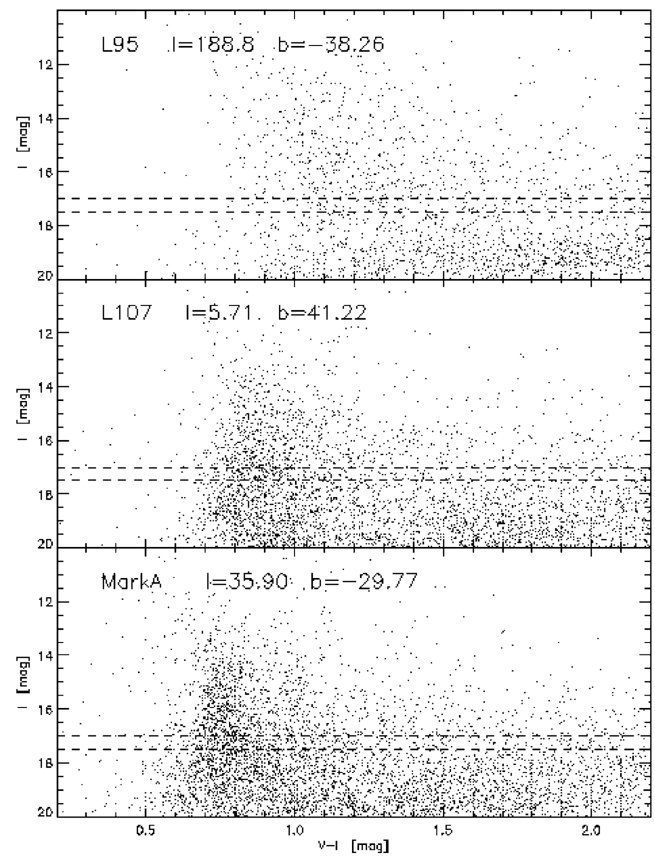

Figure 8. $(V - I, I)$ CMDs for the three fields listed in Table 3. The dashed horizontal lines show the likely range of the faint magnitude cut-off for the RVS radial velocity determinations.

stars. Additionally, information on the metal content of fainter stars will be provided by *Gaia* photometry and astrometry. Since different populations have different kinematics and metallicities, coupling these properties will allow us to distinguish statistically between thin/thick-disc and halo stars.

2.13 Age–metallicity relation

The age–metallicity relation (AMR) for disc stars, if such a relation exists, gives information about the process of star formation, about stellar orbit diffusion from scattering by molecular clouds (Francois & Matteucci 1993; Edvardsson et al. 1993) and about the time-scale for gas mixing (van den Hoek & de Jong 1997). The existence of an AMR has long been a controversial issue. Twarog (1980) found an AMR in field stars, while Edvardsson et al. (1993) derive no AMR from a sample of about 187 FG giants with known metallicity, distance and magnitude. Ng & Bertelli (1998), using revised age estimates, derive a moderate AMR with a slope 0.07 dex Gyr^{-1}. These authors find that the main source of uncertainty in the age–metallicity determination is due to the distance estimates that are used in the conversion from apparent to absolute magnitudes. On the basis of their simulations, distances need to be known with at least 5 per cent accuracy to obtain ages with a precision of about 16 per cent. *Gaia* will observe stars brighter than $M_V = 5$ with a distance accuracy of less than 1 per cent up to 1 kpc, and with an accuracy of 5 per cent up to 2 kpc. The results of Ng & Bertelli (1998) are in substantial agreement with the Rocha-Pinto et al. (2000) study of a sample of 552 stars. They derive metal content information from Strömgren photometry and ages from chromospheric activity, finding an AMR of 0.05 dex Gyr^{-1}.

Based on 5800 stars from the *Hipparcos* catalogue with ages derived from isochrones and metallicities estimated from Strömgren photometry, Feltzing, Holmberg & Hurley (2001) find an AMR only for objects younger than 2 Gyr. Recently, using isochrone fitting to derive ages and Strömgren photometry to estimate the metallicities, Nordström et al. (2004) find no AMR on a large sample of 14 000 F and G dwarfs in the solar vicinity. All the above studies, however, suffer either from the small sample of well-measured stars (Edvardsson et al. 1993; Ng & Bertelli 1998) or from uncertainties in the determination of the metal content from Strömgren photometry which is difficult to calibrate (Haywood 2002). *Gaia* will allow age estimations via accurate positions in the HR diagram. The determination of the metal content for a large sample of disc stars which will be possible using the spectra from the RVS will be an essential complement to these accurate ages in improving our knowledge of the AMR.

Finally, chromospheric activity can be calibrated as an age indicator against isochrone fitting. Chromospheric activity is expected to decline while stars are aging and can therefore be used to date stars, mainly F, G and K dwarfs. At present, this method is poorly calibrated and many uncertainties remain: first, there is intrinsic variability of stellar activity (e.g. the activity cycle in the Sun); secondly, stellar activity is caused mainly by rotation which, although it generally decreases with age, can be influenced by, for example, tidal interaction in binary systems (Kawaler 1989). The RVS data set will include thousands of eclipsing binaries (for which the uncertainty in the projection of the rotation vector along the line of sight is removed) containing F, G and K dwarfs locked in synchronous rotation with their orbital motion and spanning a wide range of orbital periods. It will thus be possible to calibrate accurately the correlation between their levels of chromospheric activity (as traced by photometry and Ca II emission cores in RVS spectra) and their rotation speed (see Section 4.3). Using the Kawaler (1989) calibration of rotational velocity against age for main-sequence stars older than 100 Myr, an uncertainty of 5 km s^{-1} in the rotational velocity will result in an uncertainty of 20 per cent in the age of a star with a rotation velocity of 50 km s^{-1}.

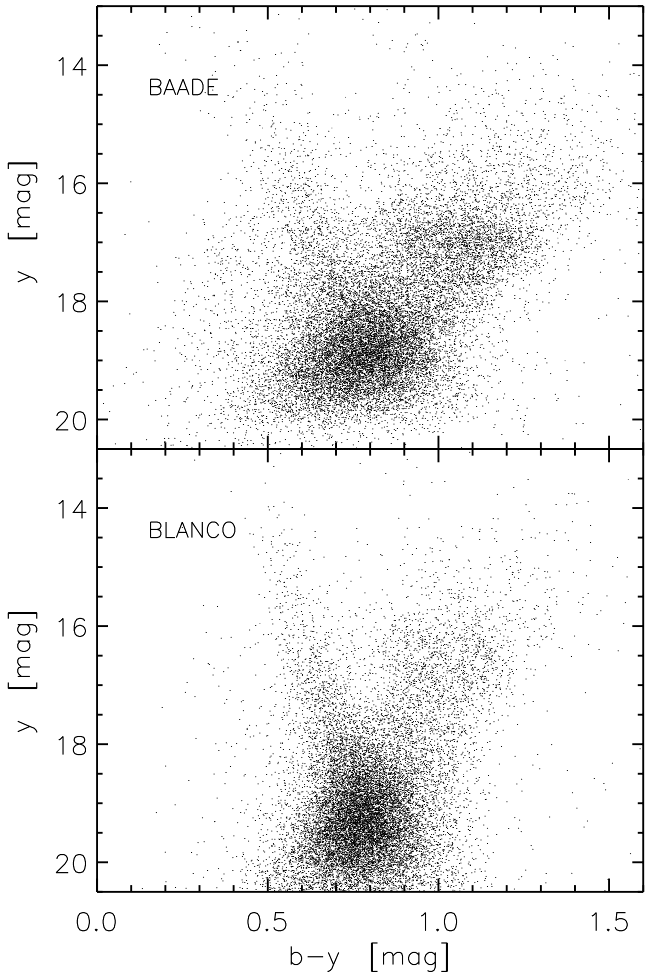

Figure 9. CMDs for a field in Baade's Window towards the globular cluster NGC 6522 (top panel) and a region in the Blanco field (bottom panel).

2.14 The Galactic bulge

The derivation of the ages, age distribution, metallicities and kinematics of the stellar populations of the bulge is extremely important for our understanding of the process of galaxy formation. As was discussed earlier, the high stellar densities along lines of sight that pass within 5°–10° of the Galactic Centre render observations of the bulge using the RVS very difficult. However, the outer bulge will still be amenable to study by the RVS and much will be learned about the nature of the bulge/bar from the RVS observations.

To obtain a more quantitative estimate of the number of stars appearing in the RVS band towards the central regions of the Galactic bulge we observed two regions, one located at $l = 0.^{\circ}99$, $b = -3.^{\circ}94$ (in Baade's Window) which contains the globular cluster NGC 6522, and one at $l = 0.^{\circ}27$, $b = -6.^{\circ}19$ (the Blanco field) which is one of the few regions of the Galactic bulge that is characterized by low reddening. We collected a series of CCD images in the Strömgren bands *u, v, b, y, Ca* with the Danish 1.5-m telescope at the European Southern Observatory (ESO) La Silla (field of view 13.7 × 13.7 arcmin^2, 0.46 arcsec pixel^{-1}). Fig. 9 shows the $(b - y, y)$ CMD for these fields. In the Blanco field we detected 2700 stars brighter than $y = 17.5$, while the Baade's Window field contains 8900 such stars (we note that the y band is the closest Strömgren filter to the RVS band); these correspond to densities of about 52 000 and 170 000 stars per square degree, respectively. The mean reddening towards both these fields is $E(B - V) \approx 0.45$. The difference in the star counts is due to the presence in the latter field of NGC 6522 and also to the fact that in this region we are looking towards the Galactic Centre.

As the figure shows, the majority of bulge stars lie well below the likely magnitude limits of the RVS in these regions. Investigations are underway to determine strategies for obtaining at least some information on the brighter stars in certain bulge fields. In the event that it is possible to obtain these data, Fig. 9 shows that bulge AGB stars would be amenable to study at magnitudes between 14 and 15. Given that the line-of-sight depth of the bulge is approximately 1 mag, a limit of 14.5 would permit the observation of AGB stars all through the bulge on these lines of sight.

Even in the absence of data close to the Galactic Centre, the RVS will illuminate certain aspects of the Galactic bulge, in particular the presence and nature of the Galactic bar. The presence of a bar may be the origin of some of the stellar moving groups observed in the solar neighbourhood. Further, there is growing evidence for the presence of bulge/bar features in the stellar distributions at larger angular distances from the Galactic Centre. For example, Hammersley et al. (2000) identified a red clump feature at $l = 27^{\circ}$ and a similar one has been identified at $l = -9.^{\circ}8$ by Babusiaux & Gilmore (2005). This feature, which is also seen in observations of OH/IR stars (Sevenster 1999) and SiO masers (Izumiura et al. 1999), may be associated with a second bar, such as are often observed in external galaxies (e.g. Erwin & Sparke 2003), or a stellar ring at a distance of 3 to 4 kpc from the Galactic Centre. Along the same lines is the work by Picaud, Cabrera-Lavers & Garzón (2003) who detect a star-count excess in near-infrared data with respect to the expected disc population at $15^{\circ} < l < 27^{\circ}$. The radial velocities provided by the RVS will help to distinguish between the possible explanations of these features. Thus, although the RVS will at best observe a limited number of bright stars in the most central regions of the Galaxy (and at worst not observe the central regions at all), it will nevertheless provide very useful constraints on the properties of the bar and bulge by observing bulge features outside 10° from the Galactic Centre.

2.15 Local Group galaxies

2.15.1 The Magellanic Clouds

The Magellanic Clouds provide a unique opportunity to study the evolution of dwarf irregular galaxies at close quarters as well as the effects of galaxy interactions (both the interactions between the clouds themselves and the external effect of the Milky Way). Spite (2002) has highlighted a number of outstanding issues regarding the Magellanic Clouds which can be addressed by the *Gaia* mission. The resolution of one of these in particular relies on the spectroscopic capabilities of the RVS: does the Large Magellanic Cloud (LMC) possess a pressure-supported stellar halo? Evidence for such a population has recently been presented by Minniti et al. (2003) using observations of 43 RR Lyrae stars in the inner regions of the LMC. The observed velocity dispersion of this stellar halo is 50 ± 10 km s^{-1} (Minniti et al. 2003), which is considerably larger than the LMC thick-disc velocity dispersion of about 20 km s^{-1}, estimated from the motions of the old LMC star clusters and intermediate-age carbon stars (van der Marel et al. 2002). The RVS will therefore be able to distinguish kinematically between members of the two populations for the RR Lyrae and metal-poor K giants with magnitudes in the range 16–17.5, as it will yield velocities for these stars accurate to better than 15 km s^{-1}. It will observe stars over the entire area of the LMC, thereby making it possible to determine whether the population is rotating – this is not currently constrained by the data of Minniti et al. (2003). The presence of such a halo has direct implications for our understanding of the formation history of the Magellanic Clouds, as it implies a similar hierarchical evolution to that of the Milky Way. It also has implications for the interpretation of the microlensing data towards the clouds. For example, Alves (2004) suggests that two of the known MACHO microlensing events might be due to lensing of LMC disc stars by stars in the putative halo, although he points out that the halo cannot account for all the observed microlensing optical depth. In addition, a comparison of the kinematics of other stellar populations with those of the carbon stars may yield further insights into the nature of the stellar bar in the LMC, which is currently unclear (e.g. Zhao & Evans 2000).

The Magellanic Clouds contain a large population of star clusters (Mackey & Gilmore 2003a,b) with integrated *V* magnitudes of about 10–13. As in the case of the Milky Way globular clusters, these are useful tracers of the mass distribution and internal kinematics of the Magellanic Clouds. The RVS will be able to obtain accurate radial velocities for all the clusters, yielding a data set of more than 50 tracers per galaxy. Given that the cluster populations extend to larger radii than other tracers, these will be invaluable in the determination of the total gravitating mass of the Clouds, thereby constraining models of their formation. The internal dynamics of the Clouds and their relationship to each other, as well as the role played by the Milky Way in their evolution, are issues that remain to be comprehensively addressed.

2.15.2 The Andromeda galaxy

The Andromeda galaxy is the other massive galaxy in the Local Group. Its stellar halo is currently the focus of considerable interest, owing to the presence of large amounts of substructure, in particular a stellar stream (Ibata et al. 2001a). Recent estimates of the total mass of the Andromeda galaxy have shown that there is no kinematic evidence for the generally held belief that Andromeda is the most massive galaxy in the Local Group: the data on tracers outside about 20 kpc favour a halo that falls off more rapidly outside 30 kpc than that of the Milky Way (Evans & Wilkinson 2000). The key difficulty facing attempts to verify this conclusion is the paucity of tracer objects in the crucial radius range from 30 to 100 kpc. At present there are only a handful of globular clusters and dwarf galaxies at these radii. Recent observations of the globular cluster population of M31 within 25 kpc have shown that roughly half of the metal-poor clusters are brighter than $V = 17$ (Perrett et al. 2002). Given that there are more than 400 confirmed globular clusters within a radius of about 30 kpc (Barmby et al. 2000) compared with about 150 at all radii within the Milky Way, it is likely that there will be about 50 clusters orbiting M31 at radii useful for probing the halo. These clusters will be spread over a large area of the sky – spectroscopic confirmation of the nature of potential cluster candidates is essential, making this programme very time-consuming from the ground. The accuracy that the RVS will be able to achieve for integrated spectra has yet to be established. However, velocity errors of about 10–15 $\mathrm{km\,s^{-1}}$ would be acceptable for constraining the halo mass of M31. RVS spectra can also be used to identify other likely cluster candidates which can subsequently be followed up from the ground.

Bright ($I \sim 16$) AGB stars belonging to the halo and intermediate-age disc populations will provide additional tracers of the M31 potential. The $\sim 10^4$ young disc stars brighter than $I = 16$ and located throughout the M31 disc will permit a detailed comparison of the stellar kinematics with the well-studied gas kinematics (e.g Braun 1991). They will also facilitate the detailed modelling of disc features such as the warp.

2.16 Serendipitous discoveries

Given the richness of the *Gaia* data set, it is to be expected that it will also throw up many surprises in the field of galactic dynamics. In addition to revolutionizing our existing picture of dynamical structures such as open clusters, moving groups, etc., many new features will undoubtedly be found. The scope for such discoveries is highlighted by a number of recent discoveries relating to the Milky Way disc, namely: (i) the detection of a population of thick-disc stars with surprising kinematics suggesting that they may have originated in the satellite galaxy the merger of which with the original Milky Way disc led to the formation of the thick disc (Gilmore et al. 2002); (ii) the identification of a ring-like structure at the outer edge of the Galactic disc (Ibata et al. 2003) which spans roughly 100° in longitude and $\pm 30^\circ$ in latitude; and (iii) the detection of an overdensity in the 2MASS all-sky M-giant catalogue which may be the remnant of an accreted dwarf galaxy (Martin et al. 2004). The detailed relationship between these observations is unclear. Helmi et al. (2003a) discuss a debris origin for the ring feature which has been shown by Yanny et al. (2003) to be a kinematically coherent structure. It has also been suggested that the overdensity identified by Martin et al. (2004) was the progenitor of the ring – however, Momany et al. (2004) suggest that the overdensity is instead related to the warp and flare in the external disc. However, what is clear is that the disc of the Milky Way has had a complicated formation history which *Gaia* will be uniquely able to probe.

While these discoveries rely on observations that probe to magnitudes fainter than the cut-off for the RVS, it is important to note that the identification of the outer ring relied on the availability of large-area photometric surveys: earlier, small-area surveys had simply overlooked its presence because of its relatively low surface density. The true nature of this structure will only be confirmed once spectroscopy is available for more of its members in order to determine its kinematic relationship to the rest of the Milky Way disc. The discovery of the new thick-disc population was based on radial velocities with accuracies of about 15 $\mathrm{km\,s^{-1}}$, a level of accuracy which will be achieved by the RVS for all the stars that it surveys. The great strength of the RVS is that any new structures that are identified will already have a wealth of kinematic data with which to determine their nature. If necessary, follow-up observations from the ground can be used to study the detailed properties of individual structures.

During its five-year lifetime, the *Gaia* satellite will observe many transient objects, such as supernovae and microlensing events (Belokurov & Evans 2003). It is intended that many such events will be identified in real time on the ground, with alerts being issued (within 24 h in the case of supernovae) to enable ground-based follow-up. RVS spectra will provide immediate classification of the brightest photometric alerts, those of greatest interest for follow-up. All photometric alerts with Cousins $I_\mathrm{C} \leqslant 14$ mag will be bright enough for *Gaia* spectroscopy to provide discriminant classification on even the single, first-epoch spectrum. Fig. 10 shows ground-based spectra, recorded with the Asiago 1.82-m telescope operating in *Gaia*-like mode, of objects most frequently appearing among those undergoing outbursts. These spectra outline the major spectroscopic differences to be expected between different classes of outburst which will trigger *Gaia* photometric alerts. Brightening in pre-zero-age main-sequence objects (like T Tau and AB Aur in Fig. 10) can lead to an increase of some magnitudes, accompanied by strong and wide Ca II emission (and weaker Paschen lines) from the circumstellar disc. The width of the emission lines in novae (Nova Cyg 2001-1 in Fig. 10) is very large, tracing the outward velocity of

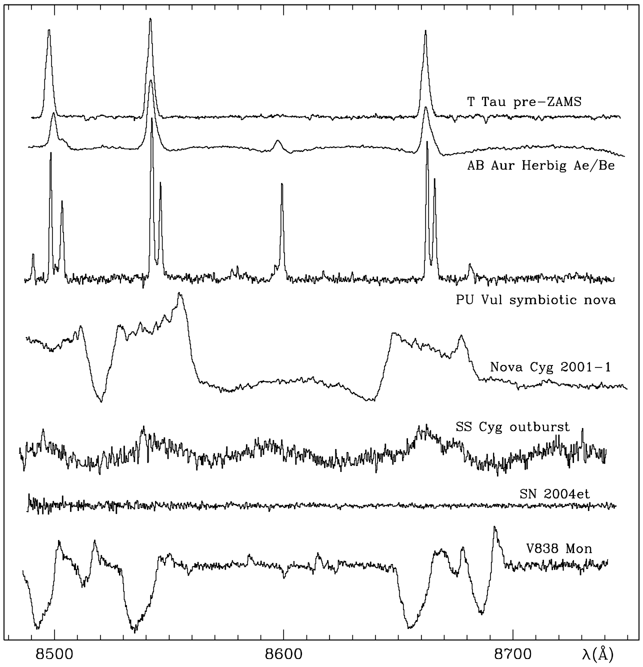

Figure 10. Examples of spectra of common classes of outburst objects for which *Gaia* will issue alerts to permit ground-based follow-up. See text for a detailed discussion.

the ejected material (of the order of 1000 km s^{-1}). Dwarf novae (SS Cyg in Fig. 10) display a smaller width connected with the lower Keplerian velocities in the accretion disc, and the emission lines in symbiotic novae (PU Vul in Fig. 10) are even narrower, tracing the small velocities of the wind from a late-type giant suddenly ionized by the burst of hard radiation from a white dwarf (WD) companion undergoing a non-degenerate thermonuclear outburst. The spectra of supernovae (Type II SN 2004et in Fig. 10) appear as flat continua, the width of the entire *Gaia* wavelength range, corresponding to a typical ejection velocity of 10 000 km s^{-1}. Finally, ejection of optically thick material gives rise to spectacular P Cyg profiles, like those displayed by V838 Mon (500 km s^{-1} terminal velocity for the spectrum in Fig. 10) later to became famous for its huge light-echo. As the figure clearly shows, RVS spectra will be able to distinguish between the different types of outburst, thereby facilitating decision-making about the necessity and urgency of ground-based follow-up.

3 BINARY STARS

Another domain in which the *Gaia* mission will bring new and extensive data is the detection, classification and complete characterization of binary systems. In this field, the RVS will be a key contributor by providing multi-epoch measurements of the radial velocity. It will impact on nearly all aspects of astrophysics where binarity is a basic quantity or provides the means to derive fundamental parameters. The statistical properties of binary stars (binary fraction, mass ratio and period distribution) will improve our understanding of the conditions of star formation in various locations in the Galaxy. Masses and radii, in addition to absolute luminosities, are fundamental inputs to stellar physics (see Section 4). A knowledge of masses for a large variety of stellar types will improve the determination of the mass–luminosity relation and directly impact on our knowledge of the initial mass function (see Section 3.2).

The difficulty of obtaining unbiased samples from ground-based observations is underlined by the significant temporal separation of Duquennoy & Mayor (1991) and Halbwachs et al. (2003) despite being Papers II and III of the same series. In Duquennoy & Mayor (1991), 37 spectroscopic orbits were derived and the binarity of solar-like stars in the solar neighbourhood was studied using a sample of 164 systems. The work of Halbwachs et al. (2003), which is based on two CORAVEL radial velocity surveys and *Hipparcos* distances, uses an original sample of about 600 stars. The limitation of both papers comes from small-number statistics. For comparison, *Gaia* will discover about 60 million binaries: more than 10^7 astrometric binaries, 10^6 eclipsing binaries, 10^6 spectroscopic binaries and 10^7 resolved binaries within 250 pc. Of these, some 10 000 will yield stellar mass determinations accurate to within 1 per cent (Arenou et al. 2002). More specifically, the RVS will be the only instrument on board *Gaia* that will be able to discover virtually all non-eclipsing binaries with orbital periods up to a month for stars brighter than $V = 14$ (Zwitter & Munari 2004). These observations will provide large and unbiased samples of binaries for a very large range of periods and mass ratios and for stars at all evolutionary stages (even the shortest lived). This will make it possible to study period and mass ratio distributions as a function of spectral type, population, formation site, etc.

The specific cases of eclipsing binary stars (Section 3.1), cataclysmic variables (Section 3.3) and symbiotic stars (Section 3.4) are detailed below.

3.1 Eclipsing binary stars

In the case of eclipsing systems, the radial velocity information will be combined with multi-band photometry to derive a complete orbital solution. Note that *Gaia* photometry alone can be used to discover much fainter binaries, but it will be limited to eclipsing systems and these are uncommon for periods longer than a few days. In addition, the RVS velocities will efficiently complement the astrometric data for the period range 0.1–5 yr (Söderhjelm 2003). The observation of eclipsing binaries by *Gaia*-RVS will be of prime importance to advances in stellar astrophysics, since stellar masses, in addition to radii and surface temperatures, can be derived with high accuracy. The distribution of parameters such as mass ratios, eccentricity and orbital periods can cast light on the various processes that have been proposed for the formation of close binary systems (Bate, Bonnell & Bromm 2002). In addition, there are aspects of the binary evolution models that are not well understood. We note that an apparent discrepancy between observations and models for binary masses near 0.8 $M_{\odot}$ has been found (Popper 1997b; Clausen, Helt & Olsen 2001). In these systems, the secondary star appears to be more evolved than the primary in both luminosity and radius. Modelling these stars is further complicated by the fact that many objects show evidence of spot activity. Good samples are needed before drawing any firm conclusions. The high resolution of the RVS spectra will allow the derivation of the statistical properties of spectroscopic binaries with an accuracy that cannot be achieved from ground-based surveys, owing to the required number of measurements.

Gaia will derive stellar masses to an accuracy better than 2 per cent (Munari et al. 2001b; Zwitter et al. 2003; Marrese et al. 2004), stellar radii with 1–4 per cent accuracy, and mass ratios with 1 per cent accuracy for more than 10^5 eclipsing binaries brighter than $V = 15$; of those at least 25 per cent will also be double-lined spectroscopic binaries, providing an enormous data base. In addition, synthetic modelling of the spectra of spectroscopic binaries using lines from both objects allows one to derive fundamental parameters such as temperature and surface gravity which can be directly compared with the results of the orbital solution. Those data can also be directly compared with stellar models on the theoretical L–$T_{\rm eff}$ plane, thereby overcoming the difficulties (for example, bolometric corrections, colour–temperature transformations, distance, reddening) that always hamper such a comparison on the observational $(B - V)$, V plane. If the stars of a binary pair have significantly different masses, then the requirement that the models fit the data for a single age provides a strong constraint. An accuracy of around 1 per cent in mass and radius is then required to retrieve accurate information about opacities, convection prescriptions and rotation (Andersen 2002). The need for additional mixing in stars has been confirmed by several authors using binary star data. We note, among others, the pioneering work by Andersen et al. (1988), the review by Andersen (2002), and the recent work by Siviero et al. (2004) who find excellent agreement between the Padova isochrones and the observed data on both components of V432 Aur. Young et al. (2001) present new evidence that the overshoot efficiency might depend on the stellar mass. All these results need to be tested on the very much larger data base that *Gaia* will provide.

Knowledge of the temperatures and radii of stars accurately determines their luminosities. Combining these with measured multicolour apparent magnitudes and allowing for reddening (Prša & Zwitter 2005) yield an accurate distance to the binary (Wilson & Wyithe 2003). Note that this method of distance determination is complementary to astrometric measurements and is limited only by the limiting magnitude of the instrument. The method has recently been used to derive a distance to the Pleiades (Munari et al. 2004) and to study the distances of objects as far as the LMC (see Fitzpatrick et al. 2003, and references therein). Results of the binary method agree well with astrometric distances for a dozen eclipsing binaries discovered by *Hipparcos* (Zwitter & Munari 2004).

3.2 Mass function determination

The stellar initial mass function (IMF) is of fundamental importance in many fields. On the one hand, the stellar mass distribution determines the evolution, surface brightness, chemical enrichment and baryonic content of galaxies. On the other hand, knowledge of the slope of the IMF and its possible variations can cast light on the physics of cloud fragmentation and the star formation processes through which different mass ranges of star are assembled.

Determining the IMF of a stellar population of mixed ages is a cumbersome affair. In fact, the IMF is usually obtained from the stellar luminosity function (SLF), i.e. the number of stars in a survey volume per magnitude interval, through knowledge of the mass–luminosity relation (MLR) in all mass ranges and of the star formation rate. In the vast majority of cases, the stellar masses cannot be directly derived and the mass has to be deduced indirectly from the luminosity and the evolutionary state of the star. Two basic approaches have been tried in the literature to derive the SLF: the first one makes use of a local volume-limited catalogue of stars with well-measured distances. The second method takes larger samples of stars from deep photometry. This latter is affected by various spurious effects, such as the Malmquist bias, imprecise determination of the completeness and unknown binary corrections (Kroupa 2001). In particular, Kroupa (1995) has shown that the significant difference between the volume-limited and magnitude-limited SLFs for the local disc population at magnitudes fainter than $M_V = 11.5$ is mainly due to the presence of unresolved binary stars.

The determination of the SLF from a volume-limited star catalogue gives more reliable results. However, to date, complete samples of trigonometric parallaxes are known only for stars brighter than $M_V \sim 9.5$ at distances $d < 20$ pc, while for the faint M dwarfs the estimated completeness distance is 5 pc (Leinert et al. 1997). This means that only a limited sample of objects is covered. A major caveat of any photometric luminosity function is that the determination of the distance relies on the photometric determination from a CMD. In practice, the determination of the IMF from the SLF requires knowledge of the chemical composition of each star, since the absolute magnitude and colour depend on both metallicity and age. Assuming solar metallicity for a metal-poor thick-disc star would lead to an underestimate of the absolute magnitude, an overestimate of the distance and thus an underestimate of the number density.

The RVS will contribute to the determination of the IMF through the accurate estimation of the binary fraction and of stellar parameters. This, together with a parallax determination, will precisely locate a star on the CMD and will allow a better determination of the stellar MLR which can subsequently be used to convert stellar luminosity functions into stellar mass functions. Our present-day knowledge of the MLR for masses lower than $1.5\,{\rm M}_{\odot}$ is based on data on visual binaries, since only a limited amount of high-quality data on double-lined eclipsing binaries and resolved spectroscopic binaries are currently available (Malkov, Piskunov & Shpil'Kina 1997).

By combining the proper motion, radial velocity information and chemical abundances of single stars, information can be derived about the dependence of the IMF on metal content. In fact, while at the upper mass end ($>10\,{\rm M}_{\odot}$) the IMF seems to be virtually independent of the metal content, a dependence has been suggested at the low-mass end (Reylé & Robin 2001) where a flatter slope has been found for thick-disc stars. However, while on the one hand the IMF of the metal-poor stars in the Galactic spheroid does not show this behaviour (Gould, Flynn & Bahcall 1998), on the other hand Zoccali et al. (2000a) derive an IMF for the metal-rich Galactic bulge which is consistent with that of the metal-poor globular clusters.

The existence, if any, of extremely metal-poor stars will cast light on the primordial IMF. Any observed variation of the IMF between different environments would suggest that cloud fragmentation based on the Jeans formulation (i.e. on gravity) is not the only mechanism at work, but rather that different processes (such as turbulence) might be important (Padoan & Nordlund 1999; Klessen 2003).

3.3 Cataclysmic variables

Cataclysmic variables (CVs) are a diverse class of short-period semi-detached binaries consisting of an accreting WD primary and (typically) a low-mass, main-sequence secondary star. They are valuable manifestations of late-stage binary evolution, which also provide a window into the fundamental physical processes associated with accretion and nova explosions (including, possibly, Type Ia supernovae). The RVS spectra will be useful for identifying CVs and will contain substantial astrophysical information on line strengths, shapes and velocity variations. CV spectra show strong and distinctive lines in the RVS band: broad ($\sim$3000 km s^{-1}, 8 nm) double-peaked Ca lines, originating in the cooler outer edges of the disc; narrow emission (from the heated face of the secondary star) or, in longer period systems where the secondary is larger and brighter in this band, photospheric absorption features instead of emission; and broad Paschen lines, one of which coincides with the Ca line at about 866 nm. The spectra vary substantially from system to system, depending on the orbital period, accretion rate and disc state. Uniquely among astrophysical objects, some of these systems show extremely strong N I lines. In magnetic CVs, the Ca triplet can be seen strongly in emission in the one or two systems studied, but very few data are available.

For the current RVS specifications, a practical limiting magnitude of $V \sim 16$ can be expected for determining CV system parameters. There are currently 140 CVs brighter than $V = 16$ (Downes et al. 2001). Extrapolating from the initial findings of the SDSS (Szkody et al. 2002), the incompleteness level is about 30 per cent on the basis of selection by colour only (which has strong selection effects). *Gaia* spectroscopy will be very sensitive in the search for signatures of accretion (line emission). This should lead to the discovery of a large number of intrinsically faint systems (possibly up to 1000). All of these CVs will have excellent parallaxes and hence luminosities. The ratios of secondary to primary masses provide an important test of population models of interacting binaries, and can be calculated from the orbital period and velocity of the secondary: for a significant fraction of CVs in the RVS sample, the binary orbit and inclination will be obtained from reflection modelling, from eclipses, or directly from the *Gaia* astrometry.

Gaia will provide a minimally biased sample of CVs for population and evolution studies. It should be noted that spectroscopy from the RVS is particularly powerful: many CVs hardly vary (the novalikes), and many systems that would be considered detached based on photometry are evidently accreting only once spectroscopy is obtained. Periods are much easier to determine with radial velocity measurements than by photometry. The spectroscopy will also pick up new classes of unexpected objects such as short period systems with K- rather than M-type secondaries. There is also the likelihood of finding longer period double-degenerate and other 'graveyard' CVs, as evolution models predict large numbers of these. In current surveys they would be indistinguishable from WDs on the basis of their colours. In addition, the RVS survey will determine the fraction with Ca emission compared with absorption, and the relationship of these with the different classes of CV (magnetic/non-magnetic), luminosity and secondary spectral type. Ultimately, information will be gained on the cause of the differing line strengths.

The Ca triplet lines are more clearly double-peaked than other strong lines in the optical spectrum because they originate in the cooler outer regions of the disc. For a large number of disc CVs, Doppler tomography will be possible. This will produce maps of disc velocities including the effects of tidal distortions and the infalling stream, and the run of Ca emission within the disc. It will also identify other aspects of disc structure, for example the spiral waves that have been seen in some dwarf novae (Steeghs, Harlaftis & Horne 1997), which have implications for our understanding of accretion discs in general. For those CVs for which data are available, many (perhaps most) seem to have narrow Ca triplet emission components. The strength of these lines and their ratios are inputs for atmospheric heating models of the secondary star. The Ca triplet is particularly good for both of the above applications: Ca velocity maps are of intrinsically higher resolution than the more commonly used Hα maps and, because Ca is less saturated than Hα, the associated atmospheric heating models are simplified (Marsh & Duck 1996).

3.4 Symbiotic stars: the supernova connection

Type Ia supernovae (SNe Ia), the only supernovae to explode in elliptical galaxies, are widely used as cosmological distance indicators. They provide a clear indication of cosmic acceleration and of a non-zero value for Einstein's cosmological constant (e.g. Perlmutter, Turner & White 1999). While current search programmes have been successful in discovering new SNe Ia at high redshift [e.g. the High-Z Supernova Search Team (HZSST) and Supernova Cosmology Project (SCP) surveys], the true nature of the SN Ia progenitors and their explosion mechanisms are still matters of investigation and debate. With look-back times of roughly half the current age of the Universe, one has to make sure that possible evolution of the progenitors is not mimicking a cosmological effect. It is generally believed that the explosion of a SN Ia is associated with a WD that grows in mass to the Chandrasekhar limit via accretion. Most of the debate about the SN Ia progenitors involves the nature of the companion feeding mass to the WD. In the *single-degenerate* scenario it is a main-sequence or giant star, while in the *double-degenerate* scenario the companion is itself a WD and the supernova explosion results from the merger of the two WDs in a binary system.

A possibility for the single-degenerate scenario is that the donor star is a late-type giant, giving rise to a symbiotic star (Kenyon 1986). Munari (1994) has listed the requirements that symbiotic stars have to possess to be viable progenitors of SNe Ia. These include: (i) their WDs must be massive enough to be able to grow to the Chandrasekhar limit by accretion of only a fraction of the mass reservoir transferable from their companions; (ii) their number in the Galaxy must be appropriate to account for the SN Ia rate given the evolutionary time-scale of the donor giant; and (iii) the symbiotic stars must be appropriately frequent among the bulge/thick-disc/halo populations of the Galaxy, which correspond to the dominant stellar populations in elliptical galaxies.

Gaia is ideally suited to address all these issues. First, *Gaia* will detect most late-type giants in the Galaxy and it will be able to discover most of those harboured in symbiotic star systems, thus providing the fractional rates within the various Galactic populations. Symbiotic star systems display a distinctive appearance in the RVS wavelength range (e.g. Schulte-Ladbeck 1988; Zhu et al. 1999; Munari & Zwitter 2002; Marrese, Boschi & Munari 2003) which, coupled with their characteristic photometric variability and spectral energy distribution, will allow the RVS to identify them easily even in low signal-to-noise ratio spectra. In fact, the cool giants in Galactic symbiotic stars are mainly of spectral types K and M, thus emitting strongly in the Ca II region, away from the veiling effect of the blue continuum emitted by the circumstellar ionized gas. This gas also shows up in the RVS spectral range by displaying strong Paschen, Ca II and He I emission lines (sometimes also useful to trace the orbital motion of the ionizing WD companion). Monitoring their radial velocities over the five-year mission lifetime (three times longer than the typical ∼600 day orbital periods), the RVS will provide orbital periods for a statistically significant number of objects. An indication of the mass ratio between the cool giant and the accreting WD can be obtained by comparing the radial velocity curve of the giant with that of the emission lines of the highest ionization states which presumably arise in the regions closest to the WD. In fact, none of the strong lines of very high-ionization levels in the spectra of symbiotic stars falls within the RVS wavelength range. However, knowing their orbital periods and phases from the combination of *Gaia* photometry and radial velocities, a small number of ground-based spectra at appropriate wavelengths and phases will suffice to determine the mass ratio for the symbiotic stars discovered by *Gaia*. These will then constrain the mass distribution function of WDs in symbiotic stars. The *Gaia* medium-band photometric bands in the red part of the spectrum have been designed to be sensitive to molecular bands. The intensity of these bands is metallicity-dependent, which yields an additional constraint on the metallicity of the symbiotic stars. Finally, the location of the symbiotic stars in the Galactic phase space, coupled with the metallicity and chemical analysis, will firmly address their relationship to the various Galactic stellar populations and thereby constrain their rate of occurrence in elliptical galaxies.

Munari & Renzini (1992) estimated the number of symbiotic stars in the whole Galaxy to be about 3×10^5, which implies that if only 2–4 per cent of them end their evolution in a supernova explosion it would account for the observed SN Ia rate. Their Galactic kinematics (Munari & Buson 1994) and infrared photometric properties (Whitelock & Munari 1992) argue that the majority of symbiotic stars are associated with the bulge/thick-disc component of the Galaxy. Evidence from energy radiated in the ultraviolet (Munari & Buson 1994) and from orbital motions suggest that a sizeable fraction of known symbiotic stars harbour massive WDs, resembling stable H-burning conditions and only minor mass loss. Thus all the ingredients seem to be in place, but it will be *Gaia* that will provide the statistically sufficient data set to address definitively the issue of whether or not symbiotic stars are viable SN Ia progenitors.

4 TOWARDS AN UNDERSTANDING OF STELLAR EVOLUTION

4.1 Introduction: RVS impact on stellar astrophysics

In spite of considerable recent efforts in the area of stellar evolution, many open problems still remain. The micro-physics of the equation of state and opacities has been tested in the range of parameters corresponding to the radiative zone of the Sun using asteroseismology. However, our knowledge of macro-physics processes such as rotation, convection and turbulence over the entire stellar mass range remains very poor. In order to improve significantly our knowledge of stellar interiors, it is necessary to couple the determination of global parameters for a statistically significant sample of stars with information from seismology (Lebreton 2000, 2002; Lebreton & Baglin 2002). Seismology needs a precise knowledge of the global parameters of the stars: luminosity, effective temperature, radii or masses in the case of binaries, surface chemical composition. In fact, seismology can be used to derive the fundamental stellar parameters from stellar oscillation frequencies (Petersen & Christensen-Dalsgaard 1996; Popper 1997a). However, if global parameters are known, stellar oscillation frequencies can be predicted and compared with the observations, giving information about the physics of the stellar interiors.

Gaia astrometry, photometry and spectroscopy will build a complete and homogeneous sample of accurate global parameters for a large range of stellar masses. The spectra from the RVS in particular can be used to derive the effective temperature $T_{\rm eff}$, surface gravity $\log g$, metallicity [Fe/H], rotational velocity $V_{\rm rot}$, chromospheric activity and interstellar extinction (see Table 1 and Paper I). When combined with parallax determinations, the luminosity, radius and mass can be obtained (Bailer-Jones 2005). The expected accuracies of the various parameter determinations are discussed in Paper I (see also Table 1). Finally, the absolute magnitudes of stars having distances measured with an accuracy of 1 per cent will be known to within 0.03 mag. The accurate placement of stars in HR diagrams will allow the construction of very precise stellar tracks and give hints about the physical processes taking place in stellar interiors.

It is well known that the location of a star in the HR diagram does not allow a unique determination of its age, since several combinations of [Fe/H], [α/Fe] and age are possible. To derive accurate ages requires very precise estimates of effective temperatures, reddening and chemical composition. For old main-sequence halo stars the expected RVS accuracy on the stellar parameters (see Table 1), combined with information from the photometric observations, will lead to uncertainties in individual age determinations of about 20 per cent. The largest contribution to this error is from the uncertainty in [Fe/H]. However, since the age determination will be made by comparing the location of the stars in the HR diagram with theoretical models, further uncertainties will come from the inadequacies of our models of the internal physics of stars (i.e. mixing, diffusion, nuclear rates, etc.). The stellar parameter determinations from *Gaia* will be therefore first be used as input to improve the stellar models.

In the following sections, we underline some of the areas where the RVS will particularly contribute to our understanding of stellar physics.

4.2 Star formation and pre-main-sequence evolution

The process of star formation in different environments is far from being understood. In particular, it is difficult to reconcile the prominent influence of the local environment (turbulence, compression, initial trigger) on small scales with the universality of the Schmidt and Kennicut law on Galactic scales [see Elmegreen (2002) for a recent review], which suggests that Galactic-scale gravity is involved in the first stages of star formation. The *Gaia* study of Galactic star-forming regions will shed light on the details and modality of star formation both in space (does the star formation take place in giant molecular clouds or in small cloudlets?), and in time (from the age distribution of stars), deriving absolute luminosities, effective temperatures, multiplicities, kinematics and, where possible, masses of the star-forming complexes.

Many aspects need to be clarified concerning the pre-main-sequence (PMS) evolution of stars. In the domain of small masses ($\leqslant 1.5\,{\rm M}_{\odot}$), the main uncertainties are related to the treatment of over-adiabatic convection, the stars being fully convective at the beginning and developing a small radiative core during the H-burning phase. The PMS tracks run almost parallel to the main sequence, starting from the deuterium-burning phase which represents the starting point of the evolution in the visible. Unless binaries are present, mass estimates rely on the assumptions of the convective model (D'Antona 1999). The prototypical PMS star of this mass range is T Tauri. During those initial stages, parameters such as stellar rotation, angular momentum evolution and magnetic field strength play very important roles which need to be quantified by observed data.

Massive stars are believed to be formed via continuous mass accretion during the PMS phase (Palla 1998). The star follows the birth-line accreting mass and, when the accretion phase stops, the object leaves the birth-line and moves towards the main sequence. This model is in agreement with several observational constraints. However, not everything is well explained. The location of the birth-line is strongly dependent on the accretion rate which is essentially unknown. The accretion rate greatly influences all the internal properties of the stars as well as the PMS lifetime (Maeder & Behrend 2002). Additionally, the accretion rate derived for low-mass stars fails to describe massive objects, since the formation time would be too long compared with the main-sequence lifetime (Norberg & Maeder 2000): stars would leave the main sequence before being fully formed.

An additional source of uncertainty for massive PMS stars is related to their high rotation velocities and to the treatment of convection (see the following sections for a detailed discussion).

Accurate distance determinations for very young associations and clusters, together with spectroscopic determination of the effective temperatures, rotational velocities and infrared spectra of PMS stars, will lead to more accurate PMS tracks.

The angular momentum budget of stars and the way in which stars lose it have not yet been fully understood. PMS stars are known to be fast rotators. In young clusters there seems to be a relation between the ages and rotational velocities of the stars, in the sense that stars appear to be losing angular momentum (Terndrup et al. 2000; Stassun & Terndrup 2003) during their lifetime. The transfer of angular momentum through the star and the role of the protostellar disc predicted by the models need to be compared with observations.

A large number of (proto)stars in the PMS phase are likely to be detected by *Gaia*, with a significant sample of all ages ranging from the earliest T Tauri phase (a few Myr) to the onset of central H burning (several tens of Myr). *Gaia* will observe about 120 young open clusters like Praesepe within 1 kpc of the Sun with an accuracy comparable to that reached by *Hipparcos* in the Hyades where low-mass PMS stars are visible. In the RVS wavelength range, the spectra of T Tauri stars show all three Ca II lines in very strong emission. This will allow for the identification of T Tauri stars even at very low signal-to-noise ratios.

4.3 Rotation

Despite the fact that many observations have demonstrated that rotation is a necessary ingredient in models of massive stars (Maeder & Meynet 2000b; Soderblom, Jones & Fischer 2001), the effect of stellar rotation on the evolution of stars has only recently been included in stellar models. Among the critical observations, we recall the fact that rapidly rotating massive O stars have peculiar He abundances. B- and A-type stars in the Magellanic Clouds are found to have large relative excesses of He/H with respect to the prediction of current models without rotation. The most likely explanation of these peculiar abundances is rotation-induced mixing. Rotation can influence the location of a star in the HR diagram, its luminosity and its lifetime. The evolution of massive stars is the result of an interplay between rapid rotation and mass loss. In fact, massive objects are rapidly rotating when they form, and as a result of the reduced internal pressure they are sub-luminous. During their main-sequence lifetime, the stars decelerate owing to angular momentum loss through their winds, and become more luminous more rapidly than non-rotating stars (Maeder & Meynet 2000b). Rotation increases the H-burning time for stars more massive than 9 $M_\odot$ by about 25–30 per cent, while the effect on the He-burning lifetime is smaller (about 10 per cent: Maeder & Meynet 2000b). The effect on age determinations is far from being negligible, amounting to about 25 per cent. In that sense, rotation can mimic the effects of core overshoot. To date, only 20 000 stars have measured $v \sin i$ (Glebocki & Stawikowski 2000). A detailed analysis has revealed that while early-type stars, from O-type to early F, are fast rotators (50–400 $\mathrm{km\,s^{-1}}$), late-type objects (from late F to M) possess lower rotational velocities ($v \sin i \leqslant 50\,\mathrm{km\,s^{-1}}$: Munari, Agnolin & Tomasella 2001a; Soderblom, Jones & Fischer 2001). PMS stars are known to be fast rotators, reaching 30 per cent of the breakup velocity – as they age, mass loss causes them to lose angular momentum. In fact, in young star clusters, a relation has been found between the age of the cluster and the distribution of rotational velocities of the stars (Terndrup et al. 2000, 2002). *Gaia* will study 120 young clusters closer than 1 kpc, allowing the determination of the rotational velocity. The interaction of the convective envelope of low-mass stars with their differential rotation sustains a magnetic field which, by trapping the ionized stellar winds, induces a loss of angular momentum from the stars.

The RVS will greatly improve our knowledge by directly measuring rotation via line broadening and spot transit for a large sample of stars: the combination of accurate luminosity, effective temperature and rotational velocity determinations provided by the RVS spectra will cast light on their evolution. Gomboc (2003) and Gomboc & Katz (2005) discuss the accuracy of the determination of $v \sin i$ from the cross-correlation of the RVS spectra of single stars. Precisions of $v \sin i \sim 5$ km $\mathrm{s^{-1}}$ should be obtained at the end of the mission for late-type stars down to $V = 15$. For B5 main-sequence stars, we expect an accuracy of $v \sin i \sim$ 10–20 $\mathrm{km\,s^{-1}}$ up to $V \sim$ 10–11. The periodic transit of spots on the stellar surface can also trace the rotation. The RVS spectra can trace several spots at once as they cross the projected surface. The associated emission lines will split according to the velocity, allowing accurate rotation measurements even with only a few tens of spectra (Munari 2003b).

4.4 Mixing processes

One of the main points of uncertainty in stellar evolution theory concerns the extent of the convectively unstable regions and associated mixing. Thermal convection arises in stars when radiation is not sufficient to carry the heat flux originating from the deep interior. The convective instability occurs wherever the local temperature gradient is steeper than the adiabatic gradient, a condition called the Schwarzschild criterion.

However, an extra mixing beyond the classical convective regions (overshoot) seems to be at work [see Chiosi (1999) for a review]. The theory of non-local convection has made significant progress over the past decade (Xiong 1990; Canuto & Mazzitelli 1992; Grossman 1996; Ventura et al. 1998; Canuto & Dubovikov 1998; Canuto 1999, 2000; Brummell, Clune & Toomre 2002; Young & Arnett 2002). However, the lack of satisfactory results means that the majority of stellar models are still calculated using the local approach of mixing-length theory [from the pioneering work by Maeder (1975) and Bressan, Chiosi & Bertelli (1981) to the recent work of Girardi et al. (2002)], where the mean free path of the convective elements is proportional to the scaleheight of the pressure H_p through a free parameter derived from comparisons with the data. Overshoot can greatly influence the evolution of massive and intermediate-mass stars, changing the lifetimes in the H- and He-burning phases, as well as the luminosity of the stars. The effect on the age determination of a stellar population is far from being negligible and is about 25 per cent for an A star of age 2 Gyr. Element diffusion can also change the evolution of a star, which can introduce errors as large as 100 Myr in the age of a 1.7-$M_\odot$ star. As far as low-mass stars are concerned, in the mass range where the core switches from the radiative to the convective regime, the determination of the overshoot parameter leads to unsatisfactory results (Woo & Demarque 2001). This corresponds to the age range of the oldest open clusters (6 Gyr), introducing large uncertainties on the age determination itself. By combining the expected *Gaia* determinations of the global parameters of stars with the results of asteroseismology measurements (see Section 4.1), it has been estimated that when L and T_eff of stars are known with a precision of about 2 per cent, then the overshoot parameter can be derived with a precision of 0.03 times the pressure scaleheight H_p (Lebreton 2000).

A discussion of the lines of observational evidence for the presence of overshoot is given by Chiosi (1998). The analysis of the HR diagram of *Hipparcos* field stars shows that the region of the so-called Hertzsprung gap is very sensitive to overshoot on the main sequence for stars with masses of 1.6 $M_{\odot}$ (Schroeder 1998). Using the data to infer the history of star formation in the disc, Bertelli & Nasi (2001) find that compatibility between the number of main-sequence and post-main-sequence stars requires some extra mixing during the core H-burning phase in stars in the range 1.5–2 $M_{\odot}$. Information about the size of the convective core can be derived from m_{He}, the maximum mass undergoing a core He flash. m_{He} can be derived from the luminosity function of the red clump stars: the mass distribution inside the clump presents a peak at m_{He} where the He-burning time in the core has a maximum (Girardi & Salaris 2001). The ratio $^{12}C/^{13}C$ in AGB stars can be derived from RVS spectroscopy and gives hints about the third dredge-up, which in turn depends on the mass-loss rate and on the treatment of convection (Marigo 2000).

Classical Cepheids provide quantitative constraints on the efficiency of mixing phenomena (rotational mixing, overshoot, semi-convection) among intermediate-mass stars (Maeder & Meynet 2000b; Cassisi 2003). The discrepancy between evolutionary masses and pulsation masses for classical Cepheids dates back to the 1970s. Recent investigations suggest that this discrepancy is at the level of 10 per cent for Galactic Cepheids (Bono et al. 2001) but of the order of 15–20 per cent for Magellanic Cepheids (Beaulieu, Buchler & Kolláth 2001). We still lack clear physical arguments to explain whether this discrepancy is a real feature or a consequence of errors in the physical assumptions adopted to construct evolutionary and pulsation models (Bono, Castellani & Marconi 2002). Suggestions have been advanced in the literature that the Cepheid mass discrepancy can be alleviated by including overshoot (Chiosi et al. 1992).

The careful calibration of the HR diagram as a function of age and metallicity by *Gaia* will give very important hints about stellar interiors and, when considered in conjunction with the results of seismology observations, will improve our capability to construct non-local convective models.

4.5 Mass loss

Mass loss from stars is important for the evolution of the interstellar medium, the composition of which depends on the nature of the supplied material. Stars are known to lose mass at various rates during different stages of their evolution. The RVS observations will be well adapted for the study of stellar winds and mass loss, since Ca II and H lines display characteristic P Cyg profiles in the RVS spectral range even for modest mass-loss rates (Munari 2003b).

In particular, mass loss is a dominant effect in the upper main sequence (Chiosi & Maeder 1986). The mass-loss rates currently used are based on observations (de Jager, Nieuwenhuijzen & van der Hucht 1988; Lamers & Cassinelli 1996). However, the relation between rotation and mass loss is not yet properly quantified. While Vardya (1985) finds a significant increase in mass loss with rotation for OB stars, only a modest increase is derived by Nieuwenhuijzen & de Jager (1988). The same uncertainty is present on the theoretical side. Whether or not mass loss influences the angular momentum seems to depend on whether it is proceeding via equatorial or polar winds [see Maeder & Meynet (2000a) for a review].

In the domain of low-mass stars, it is not yet clear whether the pulsation instability might drive the efficiency of mass loss close to the RGB tip. There is mounting empirical evidence that a substantial fraction of bright RGB stars are variables (Edmonds & Gilliland 1996). This result was strongly supported by detailed analysis of time-series data collected by microlensing experiments (Kiss & Bedding 2003; Wood, Olivier & Kawaler 2004) as well as by near-infrared surveys (Ita et al. 2002). This is a new and very interesting result because it has been suggested that these objects are excited stochastically by convection (Christensen-Dalsgaard, Kjeldsen & Mattei 2001). The unique opportunity provided by *Gaia* to measure distances and to collect homogeneous multi-band photometric and spectroscopic data for a very large sample of halo and disc RGB stars is crucial to provide a comprehensive analysis of these objects. In particular, the RVS will supply firm constraints on the role played by chemical composition and binary companions in the pulsational destabilization of K-type stars.

4.6 Variable stars

Variable stars are typically used as primary distance indicators or as stellar tracers in the Galaxy as well as in external galaxies. However, they also play a fundamental role in stellar astrophysics, because they can be easily identified and their radial velocity curves are key observables to estimate fundamental parameters such as stellar masses, radii and effective temperatures. Therefore it is not surprising that variable stars are also adopted to constrain basic physics problems such as an upper limit to the neutrino magnetic moment (Raffelt 1990; Castellani & degl'Innocenti 1993) or the existence of dark matter particles (Dearborn et al. 1990; Raffelt 2000). Moreover, they also provide the unique opportunity to compare predictions based on hydrodynamical pulsation models, evolutionary models and stellar atmosphere models. *Gaia* will play a paramount role in the field of variable stars, and this topic has already been discussed in several papers (e.g. Tammann & Reindl 2002; Bono 2003a,c, and references therein). Alongside trigonometric parallax determinations, *Gaia* will provide photometric and spectroscopic time-series data for a large number of variable stars throughout the Galactic spheroid. This will create a unique opportunity to address, on a quantitative basis, several long-standing problems. In the following, we briefly mention some of the key issues.

4.6.1 Intermediate-mass variable stars

Recent theoretical (Bono et al. 1999a; Bono, Marconi & Stellingwerf 1999b) and empirical (Tammann, Sandage & Reindl 2003; Kervella et al. 2004) results indicate that the Cepheid period–luminosity (PL) relation is not universal. In fact, both the zero-point and the slope of the optical PL relation seem to depend on the metal content. Moreover, detailed investigations of Galactic and Magellanic fundamental Cepheids (Sandage, Tammann & Reindl 2004; Kanbur & Ngeow 2004) support theoretical predictions (Bono et al. 1999a,b) concerning the non-linearity of optical PL relations when moving from short to long periods. This has not been conclusively established, however, since different theoretical predictions based on linear Cepheid models (Baraffe & Alibert 2001) and empirical approaches based on the infrared flux method (Luck et al. 2003; Storm et al. 2004) suggest a mild dependence on the metal content. More recently, theoretical predictions based on non-linear, convective models and multi-band observations suggest that the PL relation of first-overtone Galactic and Magellanic Cepheids marginally depends on metal abundance (Bono et al. 2002).

Gaia will supply a new impetus to studies of the Cepheid distance scale because it will obtain an almost complete census of Galactic Cepheids. Classical Cepheids in the period range from 6 to 16 d present a well-defined bump in both their luminosity and radial velocity curves. This feature, for periods shorter than about 9 d, is located along the decreasing branch, while for longer periods it is

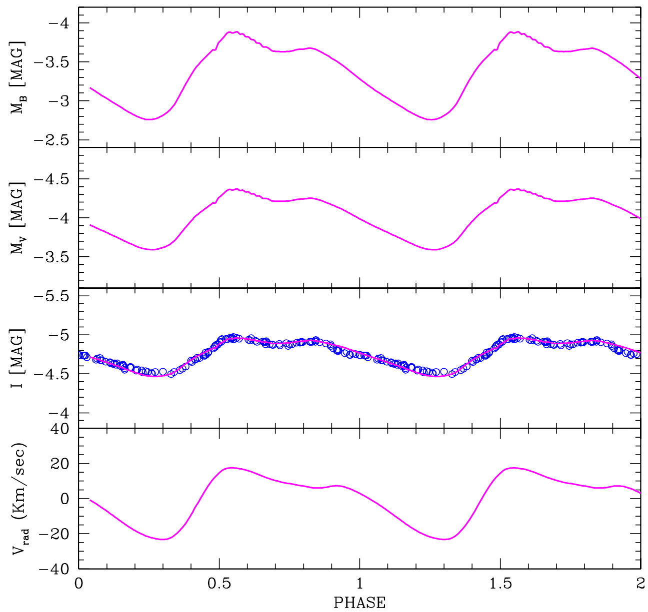

Figure 11. Predicted radial velocity and light curves in different photometric bands for an LMC bump Cepheid. A comparison with empirical *I*-band data is also shown (third panel), taken from OGLE data.

located along the rising branch. Fig. 11 presents predicted radial velocity and light curves in different photometric bands for one such bump Cepheid in the LMC. As the figure illustrates, the velocity changes will be detectable by the RVS at a statistically significant level down to a magnitude limit of about $V = 14$, where the velocity errors are below 6 km s^{-1} for single-epoch observations (Paper I). Accurate chemical compositions (intrinsic error smaller than 0.2 dex) will also be obtained down to a limiting magnitude of $V \approx$ 12–13 (Munari 2003a; Thévenin, Bijaoui & Katz 2003).

We note that the amplitude of radial velocity variations exhibited by classical Cepheids ranges from 15 to 90 km s^{-1} as one moves from short-period to long-period objects (see e.g. Udalski et al. 1999; Petroni et al. 2003). By assuming an absolute magnitude of $M_V \approx -2$ for short-period Cepheids, the RVS will thus provide accurate measurements of chemical composition, reddening and pulsation properties for all Cepheids located in the outer disc out to distances of about 6–10 kpc (depending on reddening) and over the entire Galactic disc for the brightest ones.

The current observational data set of metallicity measurements for Galactic and Magellanic Cepheids is quite limited. Accurate spectroscopic measurements of Galactic Cepheids have been recently provided by Fry & Carney (1997, 23 objects) and by Andrievsky et al. (2004, 131 objects), but only for three dozen of these Cepheids are accurate absolute distance determinations also available (Storm et al. 2004). Accurate spectroscopic measurements of Magellanic Cepheids are available for 40 objects (Luck et al. 1998; Romaniello et al. 2005), but accurate distance determinations are available only for a few of them (Gieren et al. 2000). Moreover, optical PL relations based on non-linear convective models predict that, on moving from metal-poor ($Z = 0.004$, the metal abundance typical of Small Magellanic Cloud Cepheids) to metal-rich ($Z = 0.02$, the metal abundance typical of Galactic Cepheids), there is a difference in magnitude that at $\log P = 1$ is 0.4 mag in the V band and 0.3 mag in the I band (Fiorentino et al. 2002). Empirical estimates of this effect still present a broad range of values. Using the RVS data, it will be possible to perform a robust calibration of the optical PL and period–luminosity–colour (PLC) relations [for a more quantitative discussion of both random and systematic errors, see Bono & Cignoni (2005)]. To illustrate this point, let us assume that the metallicity dependence is roughly equal to $M_V/\delta \log Z \approx |0.4|$. A series of random extractions based on the OGLE catalogue (Udalski et al. 2001) indicates that a sample of 1500 Cepheids with metal abundance ranging from $Z = 0.002$ to 0.02, and for which (i) geometric absolute distances with an accuracy better than 2 per cent ($\sim$0.04 in distance modulus), (ii) metal abundances with an accuracy better than 0.2 dex, and (iii) reddening estimates with an accuracy better than 0.02 mag are available, will allow us not only to constrain the metallicity dependence in the optical bands with an accuracy better than 0.01 mag, but also to constrain the fine structure of both the PL and PLC relations over the entire period range ($0.3 \leqslant \log P \leqslant 1.8$). At the same time, the comparison between theory and observations will supply firm constraints on the accuracy and plausibility of the physical assumptions adopted in the construction of hydrodynamical models of variable stars.

Classical Cepheids located in the outer disc are important for the distance scale and to estimate disc metallicity gradients and the shape and scale of Galactic rotation (Pont et al. 1997; Metzger, Caldwell & Schechter 1998). Note that we know the chemical composition for only two Cepheids located at distances larger than 16 kpc (Luck et al. 2003), and the radial velocities for just a handful of Cepheids in the Galactic anti-centre. The recent discovery of an extended H I spiral arm located in the fourth quadrant of the Milky Way at a radial distance of 18–24 kpc highlights the potential value of a large-volume sample of Cepheid tracers in the Galactic disc (McClure-Griffiths et al. 2004).

4.6.2 Low-mass variable stars

RR Lyrae stars are the most popular low-mass distance indicators. When compared with classical Cepheids they are at least 2–3 mag fainter but they are ubiquitous in the Galactic spheroid and in dwarf galaxies. The optical luminosity and metallicity of RR Lyrae stars are related through an M_V–[Fe/H] relation. Different aspects of this relation have been addressed in countless empirical and theoretical investigations (see Castellani 1999; Bono 2003b; Cacciari & Clementini 2003; Catelan 2004, and references therein). The calibration of this relation is still affected by uncertainties in distance estimates, reddening corrections and evolution off the zero-age horizontal branch. However, recent theoretical and empirical evidence indicates that the K-band period–luminosity–metallicity relation is only marginally affected by these deceptive uncertainties (Bono et al. 2003). Benedict et al. (2002) recently provided an accurate trigonometric parallax for RR Lyr itself based on observations obtained with the Fine Guide Sensor on board the *Hubble Space Telescope* (although they had only five reference stars). This notwithstanding, a robust calibration of both the zero-point and slope of the M_V versus [Fe/H] relation still awaits better statistics. If we assume an absolute magnitude of $M_V \approx 0.6$ at [Fe/H] $= -1.5$ (Cacciari & Clementini 2003), we find that the RVS will provide accurate measurements of chemical composition, reddening and pulsation properties for the entire sample of metal-poor ([Fe/H] $= -1.65 \pm 0.03$: Suntzeff, Kraft & Kinman 1994), halo RR Lyrae stars out to distances of about 2–3 kpc.

A further interesting aspect for which the RVS will be valuable is the detection and measurement of RR Lyrae stars in binary systems. We still lack detailed measurements of the dynamical masses of RR Lyrae stars, since at present there are only a few Galactic (Wade et al. 1999) and LMC (Soszynski et al. 2003) candidates.

Gaia will also create the unique opportunity to calibrate the PL and the PLC relations for the known Type II Cepheids, namely stars of type BL Herculis, W Virginis and RV Tauri. At present, the empirical relations are hampered by small-number statistics because only a handful of such stars have been identified in globular clusters (Pritzl et al. 2003) and in the LMC (Alcock et al. 1998). These objects are very good distance indicators because they are at least 1 mag brighter than RR Lyrae stars. In addition, theory and observations suggest that their properties depend only marginally on metallicity (Bono, Caputo & Santolamazza 1997).

5 CONCLUSIONS

The Radial Velocity Spectrometer (RVS) on board the *Gaia* satellite will provide spectra in the 848–874 nm wavelength range with a resolving power $R = 11\,500$ for stars brighter than magnitude $V = 17$ over approximately 90 per cent of the sky. The unbiased nature of this data set, combined with the multi-epoch observations of each object, render the RVS data set unique among spectral surveys of the Galaxy. In this paper, we have highlighted the many areas in which the RVS spectra constitute an essential complement to the astrometric and photometric data that *Gaia* will collect. For studies of Galactic structure and evolution, the unbiased sample of radial velocities obtained from the RVS spectra will provide the sixth phase-space coordinate which is vital for the construction of well-constrained Galactic models. The multi-epoch nature of the observations will allow the identification of large numbers of binary stars in the *Gaia* data set, while the availability of spectra taken simultaneously with the photometric observations will be invaluable for the study of detailed stellar properties, including stellar variability.

The *Gaia* mission, and the RVS in particular, will generate a data set of unprecedented size and precision which will revolutionize our understanding of all aspects of Galactic astronomy and stellar astrophysics. Harnessing the full power of such a data set presents many challenges, both practical and theoretical. For example, as we discussed in Section 2.5, the *Hipparcos* results for the local velocity distribution emphasize the difficulty of disentangling the global properties of the disc distribution function from small-scale structure such as moving groups. Given this difficulty, it will not necessarily be fruitful, or even possible, to model the *Gaia* data set via a simple decomposition into known populations such as disc, bulge and halo owing to the ambiguity in the assignment of individual stars to specific populations. Instead, a global approach will be needed, which makes simultaneous use of spatial and kinematic information to model the entire data set as a coherent unit (e.g. Binney 2005). During the coming decade, prior to the satellite launch, much work needs to be done in order to determine the iterative Galactic modelling schemes which will make optimal use of the *Gaia* data set and will lead us to a coherent interpretation of the vast quantity of information that it will contain. Similar developments will be required for the study of binaries and stellar astrophysics in the post-*Gaia* era.

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