SF2A 2009
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GAIA SPECTROSCOPY: OVERVIEW AND SYNERGIES WITH GROUND-BASED SURVEYS

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Abstract. This talk reviews the current status of the Gaia-RVS design and performance. It examines the synergies between Gaia and ground-based spectroscopic surveys. It concludes on the possible additional spectroscopic surveys that could complement Gaia in the quest for understanding the Milky-way.

1 Introduction

The first science driver of Gaia is the understanding of the structure, formation and history of our Galaxy. To fulfil this objective, Gaia will continuously scan the celestial sphere during 5 years with its 3 instruments: the astrometric instrument (providing the positions, parallaxes and proper motions), a low resolution spectrophotometer made of 2 "arms", i.e. blue and red (providing the atmospheric parameters, interstellar reddening and mean alpha elements to iron ratio) and a middle resolution spectrograph, the Radial Velocity Spectrometer - RVS (for the derivation of the radial velocities, but also for the "brightest" stars: rotational velocities, atmospheric parameters, some individual abundances and interstellar reddening). This talk reviews the current status of the RVS design (Sect. 2) and performance (Sect. 3). It examines the synergies with the current ground-based spectroscopic surveys (Sect. 4). It concludes on the possible additional spectroscopic surveys that could complement Gaia in the quest for understanding the Milky-way (Sect. 5).

2 RVS design

The Radial Velocity Spectrometer (RVS) is an integral field spectrograph, i.e. it disperses all the light that enters its 0.22 × 0.39 square degree field of view. It is a medium resolving power spectrograph, $R = \lambda/\Delta\lambda = 11\ 500$, with a 27 nm wavelength range in the near-infrared: [847,874] nm. The RVS focal plane is located on the edge of the Gaia focal plane (all the instruments share the same focal plane) and, as the other instruments, it is illuminated by the 2 Gaia telescopes. The RVS focal plane is paved with 12 red-enhanced CCDs (3 in the direction of the scan times four in the perpendicular direction). Over the 5 years of the mission, the RVS will observe on average 40 times each source (times 3 CCDs along the scan direction, for an average number of 120 spectra over the mission). The exposure time per CCD is 4.42 s, leading to an average total exposure time of ~530 s.

In late type stars, the strongest features in the RVS wavelength range is the ionised Calcium triplet. Several weak lines of e.g. Iron, Titanium or Magnesium are also present. In early type stars, the dominant lines are Hydrogen lines from the end of the Paschen series. The domain also contains weak lines, e.g. the Calcium triplet that has strongly decreased in intensity, ionised Iron, Nitrogen or Neon. The RVS domain also contains a Diffuse Interstellar Band, DIB, located at 862 nm, which unlike many DIBs seems to correlate reliably with the $B - V$ excess (Munari et al. 2008) and therefore can be used to map the interstellar reddening. Figure 1 presents 2 examples of synthetic spectra, convolved to the RVS resolving power, for a G5 (left) and a B5 (right) main sequence stars.

The full Gaia focal plane is made of 102 "science-CCDs" (of 8.847 mega-pixels each) for a total of about 902 mega-pixels. The CCDs are operated in Time Delay Integration (TDI) mode, i.e. the charges are continuously

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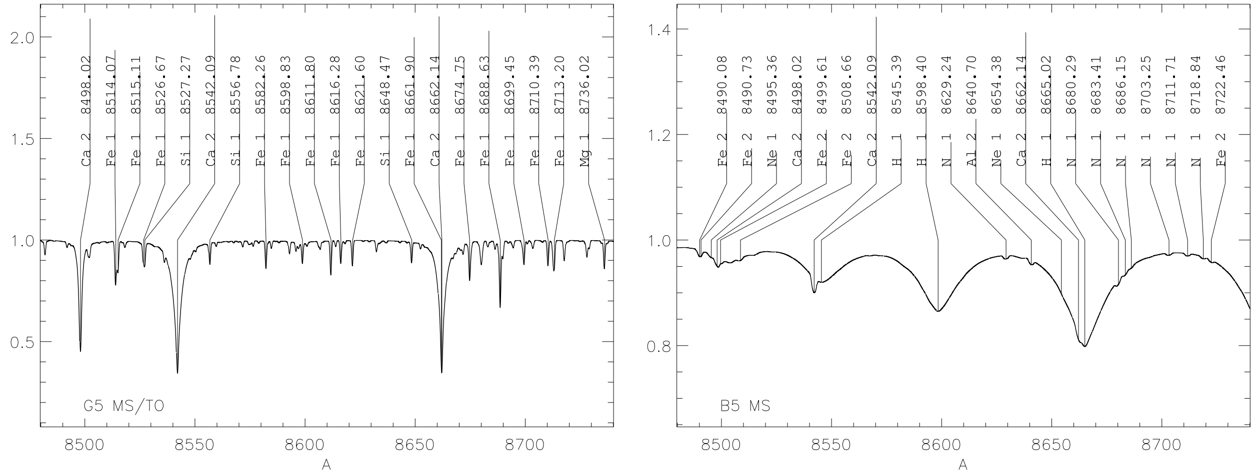

Fig. 1. Synthetic spectra of a G5 (left) and B5 (right) main sequence stars in the RVS wavelength range. The two spectra have been convolved to the RVS resolving power. The main lines are identified.

transferred through CCD columns in order to follow the sources as they cross the field of view. The antenna bandwidth is too restricted to allow for continuously transmitting the full focal plane (almost 1 billion pixels) from the second Lagrange point (at 1.5 millions kilo-meters from the Earth), where the satellite will be located. Instead, astrophysical sources are detected by the on-board software in real-time and "windows" are allocated around the objects that should be transmitted to the ground. The RVS windows are 1260 pixels long (in the spectral dispersion direction, which is also the scan direction) and 10 pixels high (in the direction perpendicular to the dispersion). Inside a window, different samplings are used depending on the magnitude of the target: the brightest sources $6 \leq \mathrm{V} \leq 8$ are transmitted in 2D full resolution, the intermediate brightness sources $8 \leq \mathrm{V} \leq 11$ are collapsed to 1D (i.e. summed over the spatial dimension) before reading and the faintest sources $11 \leq \mathrm{V} \leq 17$-18 are both collapsed in the spatial dimension and binned by group of 3 pixels in the spectral direction, in order to limit both the telemetry load and the readout noise.

There is a maximum number of windows that can be allocated at any given time. As a consequence, in dense areas, the RVS will be limited to observe the 36 000 brightest sources per square degrees. In the case of, e.g. the Baade's window, this surface density translates into a limiting magnitude for the RVS of V$\sim$13-14.

3 RVS performances

Table 1 summarises the RVS performance. The left part presents the signal to noise ratio expected for a G2V star as a function of V magnitude for (i) a single transit and (ii) at the end of the mission when all the observations will be combined. At the faint end, even the total signal collected is small and it will be possible to extract the radial velocities only from the combined information and not from a single spectrum.

The central part shows the limiting magnitude of the RVS for the different parameters that will be extracted from its spectra. The cumulative numbers of stars down to the respective limiting magnitudes are provided in the next column. It should be noted that for the atmospheric parameters and interstellar reddening, the limiting magnitudes provided in the table correspond to the limits where spectro-photometry and RVS data can be jointly used to constrain these parameters. At fainter magnitude, the spectro-photometer will still provide estimates of the atmospheric parameters and mean metallicity (with a precision of 0.2 to 0.4 dex for stars brighter than V=16 and 0.5 to 0.7 dex around V=18).

The right part recalls the specifications for the radial velocity precisions as defined in the "Gaia Mission Requirement Document - MRD" (ESA, 2006), which contains all the scientific specifications for the Gaia mission. The acronym MP stands for metal-poor and corresponds here to $[Fe/H] = -1.5$ dex.

Table 1. Summary of the RVS performance. Left: Signal to noise ratio for a G2V star as a function of magnitude, for 1 transit and for the total mission. Centre: Limiting magnitudes (and the corresponding cumulative numbers of sources) for the different parameters that will be derived from RVS spectra. Right: Radial velocity performance specifications (MP stands for metal-poor, i.e. here $[Fe/H] = -1.5$ dex).

V	S/N (per transit)	S/N (full mission)
6	150	1000
10	20	150
12	8	50
14	2	10
16		2

Parameters	V_{lim}	N stars
Vr	17-18	150-300 10^6
v sin i	13	5 10^6
Teff logg	13	5 10^6
$[Fe/H]$	13	5 10^6
$[X/Fe]$	12	2 10^6
E(B-V)	13	5 10^6

Spectral type	V	Vr (km/s)
B1V	7	1
B1V	12	15
G2V	13	1
G2V	16.5	15
K1IIIMP	13.5	1
K1IIIMP	17	15

4 Synergies with ground-based spectroscopic surveys

4.1 Gaia and RVS boundaries

The modern multiplex spectrograph technology allows ground-based surveys to complement Gaia and the RVS in the areas were they show limitations:

- In dense areas (such as the Galactic disk and bulge), the RVS will be limited to the 36 000 brightest stars per square degrees.
- The radial velocity precision in the magnitude range [15,17] is modest, e.g. ≥ 5 km.s^{-1} for a G5V star.
- In the faint Gaia magnitude range, i.e. about [17,20], the RVS will provide no radial velocities.
- For stars fainter than about 12-13, the mean metallicities provided by Gaia will have a relatively modest precision, i.e. 0.2 to 0.4 dex down to V=16 and about 0.5 to 0.7 dex at V=18.
- Individual abundances will be available only for the 2 millions brightest stars down to V=12.

4.2 Kinematical synergies

The ground based spectroscopic surveys will complement Gaia kinematics in several ways:

- The LAMOST-LEGUE (Cui, 2009) survey (2.5 millions stars over the magnitude range $17 < g < 20$ in the northern hemisphere) and SEGUE (Yanny et al. 2009) survey (240 000 stars in the magnitude range $14 < g < 20$) will provide radial velocities for stars that are too faint to be observed by the RVS and down to the Gaia limiting magnitude.
- RAVE (Zwitter et al. 2008 - several fields in the Galactic plane), APOGEE (Allende-Prieto et al. 2008 - 100 000 stars in the disk and bulge) or WINERED (Tsujimoto et al. 2008 - 1 million stars) will observe in dense areas of the sky, where the RVS observations will be affected by the overlapping with neighbouring sources and by the limitation to the 36 000 brightest stars per square degrees.

4.3 Chemical synergies

Ground-based spectroscopic surveys will also complement Gaia in the study of the chemistry of the Galaxy:

- With higher resolving powers, WINERED ($R = \lambda/\Delta\lambda = 100\ 000$), HERMES (R=30 000) and APOGEE (R=20 000) will provide finer spectroscopic information.
- With larger and/or complementary wavelength range, ground based surveys will allow to both refine the precisions on the measured abundances and to measure additional species. This is the case for WINERED ([0.9,1.35] μm), APOGEE ([1.52,1.69] μm) or HERMES ([370,950] nm).

- HERMES (1.2 millions stars in the southern hemisphere down to $V < 14-15$) and APOGEE ($H < 13.5$) will provide abundances 2 to 3 magnitudes fainter than the RVS.
- WINERED (bulge) and APOGEE (disk/bulge) will provide abundances in dense areas (where the RVS will be affected by the crowding and restricted to the 36 000 brightest stars per square degrees).

5 A need for additional complementary surveys

With several surveys showing clear synergies with Gaia (in particular LAMOST and SEGUE for the kinematic and HERMES for the chemistry), one can wonder whether additional complementary surveys are needed to support Gaia? A lot of activity, meetings, thinking, studies have taken place over the last two years, to answer this question: e.g. ESO-ESA working group on Galactic populations, chemistry and dynamics (Turon et al. 2008), the Nice (http://www.oca.eu/rousset/GaiaSpectro) and ESO (http://www.eso.org/sci/meetings/ssw2009/index.html) meetings.

From these reflexions, it appears that (at least) two additional instruments would be extremely valuable in support to Gaia:

- For the radial velocities, a LAMOST-like instrument, but located in the southern hemisphere: a low resolving power (R$\sim$5 000), a large field of view (1 or several square degrees) a high multiplexing (1000 or more fibbers). A wavelength range in the infra-red would help observing in absorbded areas. This instrument would aim to observe stars in the magnitude range $16 < V < 20$ with a precision of 1 to a few (i.e. better than 5) km.s^{-1}.
- For the chemistry, an HERMES-like instrument, but located in the northern hemisphere: a high resolving power ($20\,000 < R < 40\,000$), a field of view of the order of 1 square degree, a high multiplexing (about 500 fibbers). The wavelength range should allow for the full characterisation of the targets (i.e. derivation of effective temperature, surface gravity, micro-turbulence and mean metallicity) and for the derivation of the abundances of the key chemical species for the study of the Milk-Way chemical history. The aim of this instrument would be to observe about 1 million stars down to magnitude V$\sim$ 16.

Over the last 2 years, a lot of people have worked on defining the best ground-based strategy to support Gaia's science case. This presentation incorporates many of their ideas presented in documents, meetings or e-mail discussions. I would like to thanks the actors of these discussions, in particular F. Arenou, C. Babusiaux, O. Bienaymé, P. Bonifacio, A. Gómez, M. Haywood, V. Hill, A. Recio-Blanco, A. Robin, F. Royer, A. Siebert, C. Soubiran, F. Thévenin and C. Turon.

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