The Milky Way Unravelled by Gaia: GREAT Science from the Gaia Data Releases
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GAIA RADIAL VELOCITY SPECTROMETER PERFORMANCE

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Abstract. We present the initial performance of the *Gaia* Radial Velocity Spectrometer, providing an overview of its performance, which is essentially nominal in terms of spectral resolution, throughput and operation, except for the presence of unexpectedly high levels of scattered background. This is mainly Solar in origin, and reduces the limiting magnitude for radial velocity measurements by $\sim$1 magnitude to $V \sim 16$. Radial velocity calibration accuracies are compliant with requirements.

1 Introduction

Gaia (Lindegren *et al.* 2008) was launched on 2013 December 19, and was commissioned over the next 7 months until the handover of the satellite to ESA in July 2014. During the first part of this period, the satellite systems, such as communications, attitude control and power systems were checked out, while the scientific payload was allowed to cool in a controlled manner to its operational temperature of $\sim$160 K, with the detectors and optics maintained at slightly higher temperatures to minimise the localised condensation of contaminants on their surfaces. The payload in *Gaia* is highly integrated into the spacecraft systems, particularly for the fine guidance, and a number of complex procedures were executed successfully, and now routinely, to synchronise the spin of the satellite with the detector readout speed. Good focus was achieved from both telescopes. The elaborate process of selecting only small regions around each astronomical source for storage and telemetry to the ground operated successfully. Against this backdrop of success, three main non-conformances were found, and which compromise the scientific performance of *Gaia* to some extent: the stability of the telescope opto-mechanical system; contamination of water ice on optical surfaces affecting the

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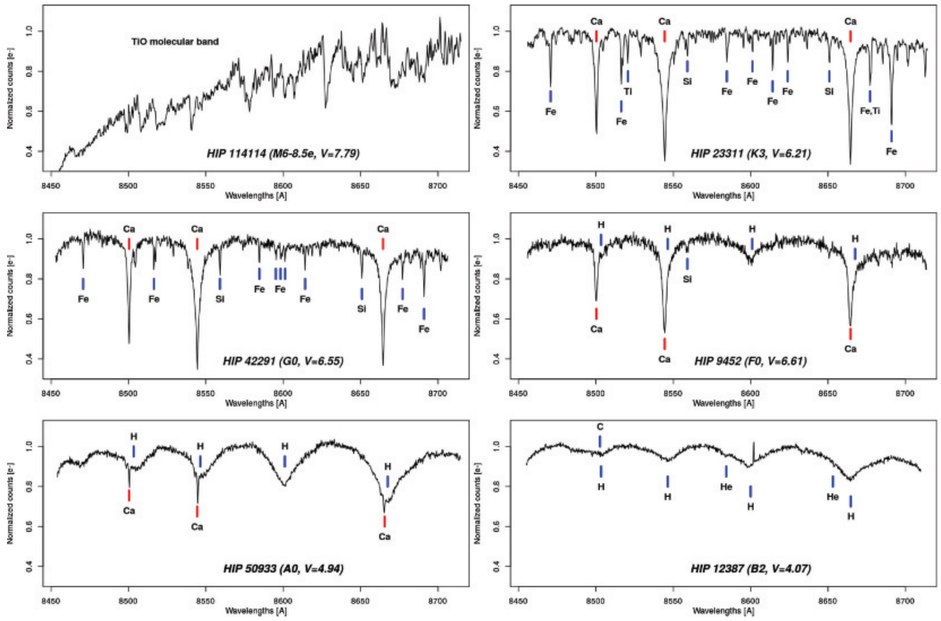

Fig. 1. RVS spectra for spectral types M to B2 with increasing temperature from top to bottom. Spectral line identifications are indicated.

overall throughput; and a higher level of scattered light in the images (see Prusti *et al.* 2015; de Bruijne *et al.* 2015 for further details).

The Radial Velocity Spectrometer (RVS) on *Gaia* provides dispersed spectra, from which astrophysical information such as temperature and the pressure of the emitting gas, as well as its metallicity, can be deduced. From the Doppler shift of the spectral lines, the radial velocity of the source can also be determined. For fainter stars, the signal-to-noise ratios in the spectra are low, and some dozens of observations must be combined to reach the required levels of accuracy. In these stars even the combined spectrum is noisy, and the radial velocity alone is determinable.

In this paper we provide a brief overview of the performance of the RVS in the first months of its operation, particularly in the context of the non-conformances found during the commissioning.

2 Nominal performances

In nominal operation, RVS produces ∼100 spectra per second, mainly of stars, but also of compact galaxies and Solar system objects. Example spectra of bright stars of different spectral types are shown in Figure 1. These show the spectral range of RVS, 8460 − 8730 Å encompassing the Ca triplet, the resolving power of $R \simeq 10\,500$ and the signal-to-noise ratio reached for a 4.4 second transit over an RVS CCD in

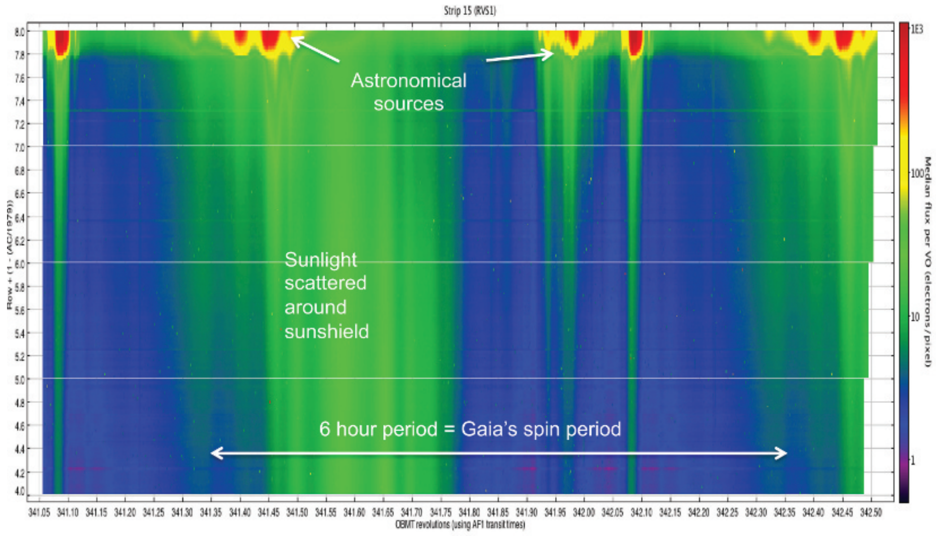

Fig. 2. The scattered light variation with time from one vertical strip of 4 RVS CCDs. The vertical is the across-scan direction, so that the image rolls out in the horizontal direction as *Gaia* rotates. Scattered light is mainly from the Sun, but astronomical sources dominate at the top of the focal plane. The colour scale is logarithmic.

the *Gaia* focal plane. The Ca triplet is strongest for stars of spectral type F, G and K, while the TiO molecular band structure is evident for cooler M stars, and the Paschen series of H is dominant in A stars and hotter. RVS single CCD spectra for these bright stars are of exceptional quality and contain abundant astrophysical and dynamical information with which to address the main *Gaia* science goals.

3 Scattered light

Because RVS does not depend on the angle between objects measured in the two telescopes, but rather on individual observations, the stability of the telescope and other optics in the RVS chain is not as critical as for astrometric measurements. Moreover, working at far red wavelengths, the contamination of the optical surfaces has less impact on the RVS throughput. However, because in RVS spectra the 270 Å spectral range is covered by ~1100 pixels, the flux levels are lower than in the other *Gaia* instruments, and hence RVS is particularly affected by the increased scattered light background. The background is dependent on *Gaia*'s spin phase, as evident in Figure 2. At certain orientations to the Sun, the background level is very significant, and that even at its lowest, the scattered light is 10× that expected. No solution has been found to reduce this, and hence this source of noise now dominates the readout noise in the RVS. Measures are being taken to re-optimise the instrument accordingly.

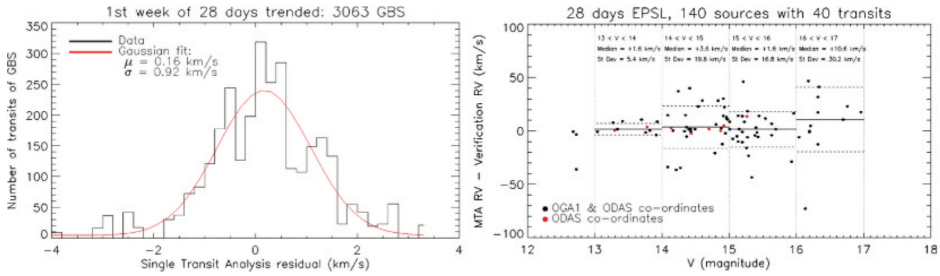

Fig. 3. (*Left*) dispersion and bias of the radial velocity residuals against ground-based measurements for bright stars after single transits of the RVS focal plane. (*Right*) radial velocity residuals for background-limited stars for 40 combined transits of the focal plane, as a function of V magnitude.

4 Bright and faint star radial velocity accuracies

The radial velocity performance for bright stars is limited by systematic effects in the wavelength calibration and in the stellar models used as templates (for example the convective shift), while for faint stars it is limited by low photon counts and background noise. Figure 3 (left) shows the residuals between the RVS radial velocity and that of a set of ground based standards (Soubiran *et al.* 2013) for single transit (integration over 3 CCD) spectra taken from data in the first week of the 28 day Ecliptic Pole Scanning Law data starting on 2014 July 25. The 1σ dispersion of the radial velocities in this sample is $0.92\,\mathrm{km\,s^{-1}}$, and the mean is $160\,\mathrm{m\,s^{-1}}$, against a specification of $1\,\mathrm{km\,s^{-1}}$ and $300\,\mathrm{m\,s^{-1}}$ respectively at end of mission (albeit for somewhat fainter stars). This compliance so early in the mission, and for a slitless instrument without internal calibration sources, indicates the satisfactory performance of the instrument and the self-calibration through the RVS data processing.

Figure 3 (right) shows the preliminary assessment of the radial velocity performance for faint standard stars (Frémat *et al.*, in prep.) as a function of magnitude, compared to their ground-based measurements. Here 40 transits per star have been combined to achieve sufficient signal-to-noise ratio. The number of standards per magnitude interval were still small at the time of that analysis. In addition, there are some contributions to the uncertainties arising from the lack of precise knowledge of the position of these standards – better than 0.1 arc sec is required, but in most cases only a coarser accuracy was available from the prior processing steps in the data analysis chain. Nevertheless, an initial assessment can be made to establish that the dispersion starts to increase above the $15\,\mathrm{km\,s^{-1}}$ specification for stars fainter than $V \sim 16$. This is $\sim$1.5 mag than the original faint star radial velocity specification, and arises from the higher background. Some improvement in this limit may be achieved through the mitigations in the onboard software for RVS indicated above.

Gaia and the RVS have been the work of a very large number of scientists, engineers and managers, in ESA, across European industry (particularly EADS Astrium, now Airbus Defence & Space), and at scientific institutes. The authors of this paper, identified for the commissioning as the CU6 Payload Experts responsible for the RVS data processing, wish to emphasise and acknowledge the contributions of this wider constituency.

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