86. Radial velocities: their acquisition

THE RADIAL VELOCITY spectrometer, or RVS, obtains spectra of all stars brighter than about $G_{\rm RVS} \sim 16$ (the magnitude in the spectroscopic bandpass). These are used to determine the radial velocity of each sufficiently bright star through its measured Doppler shift.

Together, a star's proper motion (its angular motion projected on the plane of the sky) and its radial velocity (along the line-of-sight) combine to provide the star's full three-dimensional space velocity. This is required for kinematical and dynamical studies of individual stars, as well as of larger stellar populations.

For nearby, fast-moving stars which show 'perspective acceleration' (essay #34), radial velocities are also required for a rigorous astrometric treatment. And multi-epoch radial velocity measurements provide a powerful indicator of binary or multiple star systems.

For progressively brighter stars, various other important quantities can be derived from the spectra (Recio-Blanco et al., 2016), including coarse stellar parameters (for $G_{\rm RVS} \lesssim 14.5$ mag), astrophysical information such as interstellar reddening, α-element abundances and rotational velocities (for $G_{\rm RVS} \lesssim 12.5$ mag), and even individual abundances for elements such as Fe, Ca, Mg, Ti, and Si (for $G_{\rm RVS} \lesssim 11$ mag).

THE SPECTROSCOPIC INSTRUMENT is highly integrated with the astrometric instrument (Gaia collaboration, 2016; Cropper et al., 2018). It uses the same telescopes, a dedicated section of the same focal plane, and the same sky-mapper and astrometric field (AF1) combination for object detection and confirmation. The selection of the fainter objects for observation with RVS is, however, based on an on-board flux estimate derived from the $R_{\rm P}$ photometer, which is collected just before the object enters the spectroscopic instrument field.

The radial velocity spectrometer is an integral-field spectrograph, in which the spectral dispersion of all objects in the combined field of view is achieved through an optical module (with unit magnification) in the common path of the two telescopes, actually between the final telescope mirror (M6) and the focal plane.

This module contains a blazed-transmission grating plate, four fused-silica prismatic lenses (two with flat surfaces and two with spherical surfaces), and a multilayer interference bandpass-filter plate to restrict the wavelength range to 845–872 nm.

As I detailed in essay #85, this spectral range was carefully selected to cover the important Ca II infrared triplet, which is suitable for radial-velocity determination over a wide range of metallicity, signal-to-noise ratio, temperature, and luminosity class (in particular for abundant FGK stars), and which also provides a robust metallicity indicator and stellar parameterisation.

This narrow wavelength range also covers the hydrogen Paschen series, from which radial velocities can be derived for early-type stars, as well as a prominent diffuse interstellar band (DIB), at 862 nm, which appears to be an excellent tracer of interstellar reddening.

THE DISPERSED LIGHT from the spectrometer illuminates a dedicated area of the focal plane containing 12 CCDs, arranged in three strips of four CCD rows. As a result, objects observed by the spectrometer have 43% fewer focal plane transits than in the astrometric and photometric fields, typically some 40 over 5 years.

The grating plate, with $R = \lambda/\Delta\lambda \approx 11\,700$ (giving a dispersion of 0.0245 nm per pixel) disperses images in the along-scan direction, spread over ~1100 pixels. The along-scan window size is 1296 pixels, to allow for background subtraction, and window-placement 'errors'.

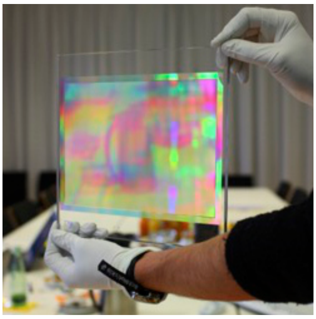
In common with the devices used throughout the focal plane, the CCDs are back-illuminated, with an image area of 4500 lines along-scan and 1966 columns across-scan. Each pixel is 10 μm × 30 μm, corresponding to 58.9 × 176.8 milli-arcsec on the sky. As with the astrometric and photometric fields, the CCDs are operated in time-delayed integration (TDI) mode: photoelectrons are integrated over the CCD as the images cross the focal plane, perfectly synchronised with the spacecraft spin.

For the radial velocity spectrometer (as well as the $R_{\rm P}$ photometers) the CCDs are red-enhanced, including an anti-reflection coating centred on 750 nm.

For the majority of objects, the spectra are binned on-chip in the across-scan direction over 10 pixels, to form one-dimensional along-scan spectra. Single-pixel-resolution windows (of size 1296 × 10 pixels^2) are only retained for stars brighter than $G_{\rm RVS} = 7$ mag.

The object-handling capability of the radial velocity spectrometer is limited to about 35 000 objects per square degree. In areas exceeding this stellar density, only the brightest objects are allocated a detector window. As for the photometers, the data quality is progressively compromised in dense areas by contamination and blending from nearby sources.

The processing of the RVS data is carried out, on the ground, within an extensive and dedicated processing 'pipeline', described for Gaia DR2 by Sartoretti et al. (2018), and for Gaia DR3 by Katz et al. (2022).



RVS grating demonstrator model (Airbus Defence and Space)

The pipeline takes care of the basic spectroscopic calibrations, including the wavelength scale, geometric calibration of the focal plane, the treatment of straylight, and the effects of CCD charge-transfer-inefficiency.

The noise-dominated faint object transit spectra are subsequently 'stacked' to derive mission-average radial velocities through cross-correlation techniques. For the brightest subset, epoch spectra and epoch radial velocities are preserved. Iterations between calibrations and source parameters are performed entirely within the RVS pipeline.

For the vast majority of (faint) stars, the individual spectra are too noisy to derive transit-level radial velocities. As a result, a single, end-of-mission composite spectrum will be constructed by co-adding the spectra collected during all of the RVS CCD crossings obtained throughout the mission lifetime.

A single, mission-averaged radial velocity is then extracted from this composite spectrum by cross-correlation with a synthetic template spectrum. The cross-correlation method finds the best match of the observed spectrum to a set of predefined synthetic spectra (e.g. with different atmospheric parameters) and subsequently assigns the astrophysical parameters of the best-fit template to the observed target.

For the few million brightest targets, single field-of-view transit spectra will be retained to derive associated epoch radial velocities. For this subset, the radial velocities of the components of (double-lined) spectroscopic binaries is also being estimated.

Radial velocity spectrometer results in Data Release 3	
Sources with radial velocities	33 812 183
Sources with mean $G_{\rm RVS}$-band magnitudes	32 232 187
Sources with rotational velocities	3 524 677
Mean RVS spectra	999 645
Variables with radial-velocity time series	1 898
Astrophysical parameters from RVS spectra	5 591 594
Chemical abundances from RVS spectra	2 513 593
Diffuse interstellar band in RVS spectra	472 584

This brief summary cannot do justice to the considerable effort, by scientists and engineers, in designing, optimising, constructing, and processing the data from the RVS system (e.g. Cropper et al. 2018).

Today, August 2022, Gaia is 8 years into its data collection phase, having been extended beyond its initially foreseen operational lifetime of 5 years in view of its spectacular performances. Hopefully it will remain operational for a total of around 10 years, limited only by its (cold-gas) attitude control system.

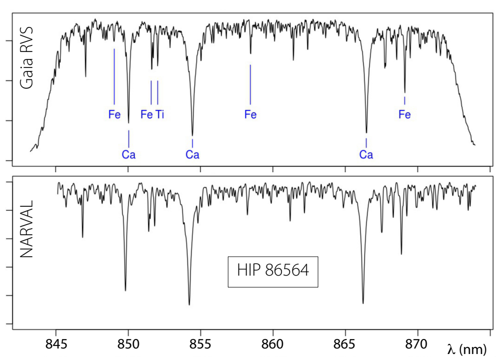
Meanwhile, results for only the first 34 months of mission data (Jul 2014–May 2017) have been processed and released by the Gaia Data Processing and Analysis Consortium, as Gaia Data Release 3 on 13 June 2022.

Along with 1.8 billion sources with astrometric data, the table above summarises the current radial velocity results. My essay #76 gives a summary of the other DR3 results, while the `ESA Gaia www pages` provide more complete and other supplementary information.

The figure shows the first public RVS spectrum, the $V = 6.7$ mag K5 star HIP 86564 from a single 4.4 sec exposure (top), and with the NARVAL spectrograph at the Observatoire du Pic du Midi (convolved to the same spectral resolution, bottom). Along with the prominent Ca triplet, lines of Fe and Ti are also visible.

Already dwarfing previous spectral surveys, and with Data Release 4 expected to contain more than 100 million radial velocities, an exceptional resource for Galactic science awaits the world's astronomers!

I will return in my next essay, #87, to look more at the scientific results from RVS contained in Data Release 3.



Cropper et al. (2018)