

COMMISSION 30

RADIAL VELOCITIES

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Stellar Radial Velocity Bibliography
Radial Velocity Standards
Catalogue of Orbital Elements of
Spectroscopic Binary Systems (SB9)

TRIENNIAL REPORT 2009-2012

1. Introduction

The past three-year period has seen steady efforts to collect large numbers of radial-velocity (RV) measurements, as well as important applications of radial velocities to astrophysics. Improvements in precision continue to be driven largely by exoplanet research. A workshop entitled “Astronomy of Exoplanets with Precise Radial Velocities” took place in August of 2010 at Penn State University (USA), and was attended by some 100 researchers from around the world. The meeting included thorough discussions of the current capabilities and future potential of the radial velocity technique, as well as data analysis algorithms to improve precision at visible and near-infrared wavelengths.

While most of these discussions were focused on the search for and characterization of exoplanets, it is clear that more classical applications of radial velocities are also benefiting from the improvements, as evidenced by recent work on binary stars described herein. Below is a summary of other activity in the field of radial velocities during this triennium. Due to space limitations, we include only a selection of efforts and results in this area.

2. Large-scale radial-velocity surveys (T. Zwitter and G. Torres)

The RAdial Velocity Experiment (RAVE; <http://www.rave-survey.org>) is an ongoing international collaboration of ~60 scientists from nine countries, led by M. Steinmetz from the AIP in Potsdam. It is continuing to use the UK Schmidt telescope at the Australian Astronomical Observatory to record a large unbiased sample of stellar spectra selected only by their *I*-band magnitude. During this triennium RAVE publicly released

its full pilot survey Siebert *et al.* 2011a, which contains 86,223 RV measurements for 81,206 stars in the southern hemisphere. In addition, stellar parameters for 42,867 of the stars were published. Altogether RAVE has already collected over 500,000 spectra, with approximately 10% of the observing time being devoted to repeat observations. The mean radial velocity error is $\sim 2 \text{ km s}^{-1}$, and 95% of the measurements have an internal error better than 5 km s^{-1} . This can be combined with distances based on 2MASS photometry, spectroscopically determined values of the stellar parameters, and stellar isochrone fitting (see Breddels *et al.* 2010, Zwitter *et al.* 2010, Burnett *et al.* 2011). Such distances are accurate to $\sim 20\%$ and cluster around 300 pc for dwarfs and 1 or 2 kpc for giants.

This collection of information allows comprehensive studies of the kinematics of our part of the Galaxy, as well as its structure and formation history. RAVE is suited to searching for stellar streams, some of which are remnants of dwarf galaxies that merged with the Milky Way during galaxy formation. A new stream, dubbed the Aquarius stream, is an example of such remnants that can be found with RAVE (Williams *et al.* 2011). Another kind of stellar streams, known as moving groups, are born inside our Galaxy. New members of nearby moving groups have been found in RAVE (Kiss *et al.* 2011), and the survey promises to reveal more in the future. RAVE allows for efficient searches for the very first stars (Fulbright *et al.* 2010), and enables the detection of interesting trends in the motions of the stars in the vicinity of the Sun (Siebert *et al.* 2011b). The survey is well suited to study our Galaxy's thick disk. Two recent studies from RAVE (Wilson *et al.* 2011, Ruchti *et al.* 2011) have focused on uncovering its origin. The survey will continue in 2012.

Another large-scale survey released during this triennium that includes radial-velocity measurements (albeit of low precision) for vast numbers of stars is SEGUE (Sloan Extension for Galactic Understanding and Exploration). A paper by Yanny *et al.* (2009) describes these spectroscopic results, which are based on some 240,000 low-resolution ($R \sim 1800$) spectra of fainter Milky Way stars down to a magnitude limit of $g \approx 20.3$. One of the goals is to enable studies of the kinematics and populations of our Galaxy and its halo. The RV precision varies from 4 km s^{-1} at the bright end ($g \approx 18$) to 15 km s^{-1} at the faint end. In addition to the velocities, atmospheric parameters including effective temperature, surface gravity, and metallicity were derived for the stars with suitable signal-to-noise ratios. The individual spectra along with associated parameters are publicly available as part of the Sloan Digital Sky Survey Data Release 7.

3. The role of radial-velocity measurements in studies of stellar angular momentum evolution and stellar age (S. Meibom)

Radial-velocity measurements with multi-object spectrographs have played a critical role in defining the mile-posts that are the foundation for much of our understanding of the time-evolution of stars. These mile-posts are star clusters — coeval, cospatial, and chemically homogeneous populations of stars over a range of masses for which the age can be determined well by fitting model isochrones to single cluster members in the color-magnitude diagram (CMD). However, the inherent qualities of clusters can only be fully exploited if pure samples of kinematic members are identified and characterized. This can be accomplished most securely and effectively with radial-velocity measurements (e.g., Geller *et al.* 2008, Hole *et al.* 2009).

Recent dedicated photometric surveys for stellar rotation periods in young clusters have begun to see dependencies of stellar rotation on stellar age and mass. These

dependencies guide our understanding of the angular momentum evolution of FGK dwarfs by determining the mass- and time-dependence of their rotation periods. Over the past three years such surveys have been combined with radial-velocity surveys for cluster membership and binarity in open clusters with different ages, revealing well-defined relations between stellar rotation period, color (mass), and age not previously discernible (Meibom *et al.* 2009a, Meibom *et al.* 2011a, Meibom *et al.* 2011b). These relations offer crucial new constraints on internal and external angular momentum transport and on the evolution of stellar dynamos in late-type stars of different masses.

Furthermore, stellar rotation has emerged as a promising and distance-independent indicator of age (“gyrochronology”; Kawaler 1989, Barnes 2003, Barnes 2007), and open clusters fulfill an important role in calibrating the relation between age, rotation, and mass. Indeed, open clusters can define a surface in the three-dimensional space of stellar rotation period, mass, and age, from which the latter can be determined from measurements of the former two. It is critical, however, to establish the cluster ages from CMDs in which non-members have been removed and single members identified. It is also important to identify short-period binaries where tidal mechanisms may have modified the stellar rotation. Radial velocities are an efficient and proven technique to identify both single and short-period binary members. The tight mass-rotation relations seen in clusters over the past three years reflect the powerful combination of time-series spectroscopy for cluster membership and time-series photometry for rotation periods.

4. Radial velocities in open clusters (R. Mathieu)

Studies of kinematic membership and binarity in open clusters based on radial-velocity measurements have a long history. During this triennium the WYIN Open Cluster Study (WOCS; Mathieu 2000) has continued to acquire intermediate-precision ($\sigma_{RV} = 0.4 \text{ km s}^{-1}$) radial-velocity measurements on its core open clusters. Currently the project has in hand a total of more than 60,000 measurements of some 11,800 stars in the open clusters M34, M35, M37, M67, NGC 188, NGC 2506, NGC 6633, NGC 6819, and NGC 7789. Some of these data and associated results have already appeared in the literature (Geller *et al.* 2008, Geller *et al.* 2009, Geller *et al.* 2010, Hole *et al.* 2009, Meibom *et al.* 2009a, Meibom *et al.* 2009b, Meibom *et al.* 2011b).

Particularly notable progress has been made on understanding the nature of blue stragglers in the open cluster NGC 188 (Mathieu & Geller 2009, Geller & Mathieu 2011). Sixteen of the 21 blue stragglers are spectroscopic binaries. These binaries have a remarkable eccentricity versus log period distribution, with all but two having periods within a decade of 1000 days. The two short-period binaries are double-lined, one of which comprises *two* blue stragglers. A statistical analysis of the single-lined binary mass functions shows the secondary mass distribution to be narrowly confined around a mass of $0.5 M_{\odot}$. The combination of these results strongly suggests a mass-transfer origin for the blue stragglers, leaving behind white dwarf companions. However, the shortest period binaries are certainly the product of dynamical encounters, leaving open the possibility of collisional origins for those blue stragglers.

5. Toward higher radial-velocity precision (F. Pepe, C. Moutou, C. Lovis)

Broadly speaking, this period has been characterized by three general trends regarding precise radial-velocity measurements as applied to exoplanet research. Firstly, the precision has been pushed to its limits such that very small RV signals even below 1 m s^{-1}

have now been detected. This capability has revealed a large population of super-Earths and Neptunes, demonstrating that they are common around solar-type stars in the Milky Way (Howard *et al.* 2011, Mayor *et al.* 2011). Secondly, Doppler shift measurements have become a tool complementary to other techniques, and in particular to the transit method of detecting exoplanets. And thirdly, RVs are moving into the near-infrared domain. The combination of red wavelengths and very high spectral resolution has only become available in recent years, but has already brought on previously unavailable opportunities for the observation of stars that are very young, very active, or of very late spectral type, and opened up possibilities for the detection of planetary signatures among those stars.

Recent developments have demonstrated that at the few m s^{-1} level the star is not necessarily the limiting factor, and that there is good reason to aim for *sub*- m s^{-1} instrumental precision (see, e.g., Pepe *et al.* 2011) provided the star is chromospherically quiet and that photon noise is not the limit. Considerable progress has been made on instrumental issues. One of the limiting factors has been the non-uniform illumination of the spectrograph, where even the use of (circular) fibers does not remove this problem entirely. Non-circular fibers have shown great promise for their scrambling properties, although much of this work has not yet appeared in the literature. One exception is the study by Perruchot *et al.* (2011) with octagonal-section fibers. Using these devices it has been possible to improve the RV precision on the SOPHIE spectrograph mounted on the 1.93 m OHP telescope from about 8 m s^{-1} to 1.5 m s^{-1} . The other important factor limiting instrumental precision is the wavelength calibration. The two main techniques used for this (thorium-argon lamps, and the iodine cell method) have a limited wavelength coverage, suffer from line blending, and have other drawbacks (including large dynamic range for the lines and limited lifetime of hollow-cathode lamps, and light absorption as well as sensitivity to ambient conditions for the iodine cell). The use of laser frequency combs as a path to achieving cm s^{-1} precision has been explored for several years, and a number of these systems are now under development for both visible (Osterman *et al.* 2007, Steinmetz *et al.* 2008, Li *et al.* 2009) and infrared wavelengths (Osterman *et al.* 2011, Schettino *et al.* 2011). Challenges still remain, but the expectation is that these devices will be available on several telescopes around the world on a timescale of a few more years.

The problems posed by the spectrograph illumination and wavelength calibration will likely be solved soon. Present-generation spectrographs are already implementing solutions to those challenges based on the technologies mentioned above. At the cm s^{-1} level, however, stellar “jitter” will still be an important source of error. Current efforts to overcome this have focused on filtering the stellar noise contribution (*p* modes, granulation, activity) by applying optimal observation strategies (see, e.g., Dumesque *et al.* 2011). Future planet search programs requiring extremely high precision will likely have to pre-select targets with very low or very well-known stellar jitter, so that these effects either have minimal impact on the RVs, or can be modeled and removed. And of course, beating down photon noise in the search for Earth-like planets will require ever larger telescopes, or restricting the searches to relatively bright stars.

Achieving very high velocity precision in the near-infrared has so far lagged behind the optical regime. Performance at the m s^{-1} has not yet been achieved, although 5 m s^{-1} has been demonstrated in a few cases (e.g., Bean *et al.* 2010, Figueira *et al.* 2010). The problems to be overcome include the treatment of telluric lines, detector technology, and cryogenic optics.

Several new radial-velocity instruments are presently under construction that should come online in the next few years. A non-exhaustive list with an indication of the

wavelength regime, telescope on which they will be mounted, and expected first-light date includes HARPS-N (visible, TNG, 2012), PEPSI (visible, LBT, 2012), GIANO (IR, TNG, 2012), HZPF (IR, HET, 2013), CARMENES (visible-IR, 3.6 m Calar Alto, 2014), SPIROU (IR, CFHT, 2015), and ESPRESSO (visible, VLT, 2016).

6. High-precision radial velocities applied to studies of binary stars

(G. Torres)

As indicated above, one of the procedures used in exoplanet research for ensuring high precision in the radial-velocity measurements relies on an iodine cell in front of the spectrograph slit to track instrumental drifts and changes in the point-spread function that normally lead to systematic errors (see, e.g., Marcy & Butler 1992, Butler *et al.* 1996). Some years ago Konacki (2005) extended the iodine technique to composite spectra, showing that precisions of a few tens of ms^{-1} can be reached in selected double-lined spectroscopic binaries. This enables considerably higher precision to be obtained for the masses of binary stars than has usually been achieved (see also earlier work by Lacy 1992).

A recent study by Konacki *et al.* (2010) focused on a handful of favorable (nearly edge-on) binaries, and combined spectroscopy with long-baseline interferometric observations, which yield the inclination angle of the orbit, to achieve record precision for one of their systems, HD 210027. Relative errors in the masses are as low as 0.066%, the smallest obtained for any normal star. Other studies by the same group have also reached very small uncertainties (Helminiak & Konacki 2011, Helminiak *et al.* 2011), made possible by the much improved velocities using their technique. The precision of the masses of HD 210027 rivals that of the best known determinations in double neutron star systems, measured by radio pulsar timing.

7. Doppler boosting effect (T. Mazeh)

In the last two years a new type of stellar radial-velocity measurement has emerged, based on the photometric beaming (aka Doppler boosting) effect. This causes the bolometric flux of a star to increase or decrease as it moves toward or away from the observer, respectively. The magnitude of the beaming effect is approximately $4V_r/c$, where V_r is the stellar radial velocity and c is the speed of light, and is therefore on the order of 10^{-3} to 10^{-4} of the stellar intensity for a solar-type star with a stellar secondary and a period of 10 days or so.

While the beaming effect had been observed previously from the ground in one or two very favorable cases (e.g., Maxted *et al.* 2000), the availability of a quarter of a million very precise, continuous light curves produced by the *CoRoT* and *Kepler* missions has opened the door to the detection of new binary systems by this method (see also Loeb & Gaudi 2003, Zucker *et al.* 2007, Faigler & Mazeh 2011). Seven new *non-eclipsing* binaries with orbital periods between 2 and 6 days have already discovered by this effect in the *Kepler* data, and were confirmed by classical spectroscopic radial-velocity measurements (Faigler *et al.* 2011). The effect has now also been seen in ground-based photometry of two extremely short period double white dwarf eclipsing binaries with periods of 5.6 and 0.2 hours (Shporer *et al.* 2010, Brown *et al.* 2011), as well as in other eclipsing systems observed by *Kepler* that also contain white dwarfs (van Kerkwijk *et al.* 2010, Carter *et al.* 2011, Breton *et al.* 2011).

8. Working Groups (H. Levato, G. Marcy, D. Pourbaix)

Below are the reports of the three active working groups of Commission 30. Their efforts are focused on providing a service to the astronomical community at large through the compilation of a variety of information related to radial velocities.

8.1. *WG on Stellar Radial Velocity Bibliography (Chair: H. Levato)*

This WG is a very small one that was created with the purpose of continuing the cataloging of the bibliography of radial velocities of stars made by Mme Barbier in successive catalogues until her retirement in 1990 (see Barbier-Brossat *et al.* 1990).

The new compilation was started late in 1990. The first version of the catalogue after the retirement of Mme Barbier was published for the 1991–1994 triennium. The catalogue is updated every six months at the following web page:

<http://www.icate-conicet.gob.ar/basededatos.html>

During the 2009–2011 period the WG searched 33 journals for papers containing measurements of the radial velocities of stars. As of December 2010 a total of 198,063 entries had been cataloged. By the end of 2011 this is expected to increase to about 285,000 records. It is worth mentioning that at the end of 1996 the number of entries was 23,358, so that in 15 years the catalogue has grown by more than an order of magnitude. The main body of the catalogue includes information about the technical characteristics of the instrumentation used for the radial velocity measurements, and comments about the nature of the objects.

The future of radial velocities is becoming very attractive and the same time more complex. Large numbers of new radial velocity measurements are expected to be published, and it may be necessary to discuss if the present approach is the best way to keeping a record of the bibliography of radial velocity measurements.

8.2. *WG on Radial Velocity Standards (Chair: S. Udry)*

During this triennium significant progress has been made towards establishing lists of stars that can serve as radial-velocity standards, to a much higher level of precision than lists that have been used in the past. Two main efforts have taken place.

One was summarized by Crifo *et al.* (2010), who report the compilation of an all-sky list of 1420 relatively bright (mostly $V \approx 6$ –10) stars developed specifically for use by the Gaia project, but which is of course very useful to the broader community. The list is based largely on measurements published by Nidever *et al.* (2002), Nordström *et al.* 2004, and Famaey *et al.* (2005). The radial velocities of most these stars are believed to be accurate at the $\sim 300 \text{ m s}^{-1}$ level, and a large fraction of them are being re-observed at higher precision with modern instruments (SOPHIE, NARVAL, CORALIE; see Chemin *et al.* 2011). It is expected that the accuracy will be improved to 100 or possibly 50 m s^{-1} when this task is concluded. A link to this list of potential standards is available on the Commission web page.

A parallel effort reported by Chubak & Marcy (2011) has been carried out by the California Planet Search group using the HIRES spectrometer on the Keck I telescope. They present radial velocities with an accuracy (RMS compared to present IAU standards) of 100 m s^{-1} for 2086 stars of spectral type F, G, K, and M based on some 29,000 spectra. Additional velocities are presented for 132 RV standard stars, all of which exhibit constant radial velocity for at least 10 years, with an RMS less than 10 m s^{-1} . All velocities were measured relative to the solar system barycenter and are placed on the velocity zero-point scale of Nidever *et al.* (2002). They contain no corrections for convective blueshift

or gravitational redshift. An innovation was to determine a secure wavelength zero-point for each spectrum by following the suggestion of Roger Griffin in using telluric lines (the origin of the iodine cell concept). Specifically, they used the telluric A and B bands at 7594–7621 Å and 6867–6884 Å, respectively, which were present in all of the spectra. This allows to correct for small changes in the CCD position, the spectrometer optics, and guiding errors for the specific observation of the program star.

There is a significant overlap between the lists of Crifo *et al.* (2010) and Chubak & Marcy (2011), providing excellent radial velocity integrity for the stars in common. It is expected that the combination of these lists will serve as standards for studies of long-period binary stars, star cluster dynamics, and for surveys of the chemical and dynamical structure of the Galaxy such as SDSS, RAVE, Gaia, APOGEE, SkyMapper, HERMES, and LSST.

8.3. *WG on the Catalogue of Orbital Elements of Spectroscopic Binaries (SB9) (Chair: D. Pourbaix)*

At the 2000 General Assembly in Manchester, a WG was set up to work on the implementation of the 9th Catalogue of Orbits of Spectroscopic Binaries (SB9), superseding the 8th release of Batten *et al.* (1989) (SB8). SB9 exists in electronic format only. The web site (<http://sb9.astro.ulb.ac.be>) was officially released during the summer of 2001. This site is directly accessible from the Commission 26 web site, from BDB (in Besançon), and from the CDS, among others.

Substantial progress have been made since the last report, in particular in the way complex multiple systems can be uploaded together with their radial velocities. The way data weights can be supplied has also been improved.

As of this writing the SB9 contains 3039 systems (SB8 had 1469) and 3784 orbits (SB8 had 1469). A total of 623 papers were added since August 2000, with most of them coming from *outside* the WG. A significant number of papers with orbits still await uploading into the catalogue. According to the ADS, the release paper (Pourbaix *et al.* 2004) has received 152 citations since 2005. This is about three times more than the old Batten *et al.* catalogue over the same period, with the SB8 still being cited in the current literature.

The important work of cross-checking the identification of systems is carried out by the CDS (Strasbourg). Indeed, with the SBC9 identifier now added to SIMBAD, each new release of the SB9 tar ball is cross checked for typos prior to integration at the CDS. Whereas some of these mistakes are ours, some authors share the responsibility as well. Users have also helped in pinning down some problems.

Although this work is very welcome by the community (about 500–1000 successful queries received every month, with 50 distinct IP addresses over the past month) and some tools have been designed to make the job of entering new orbits easier (input file checker, plot generator, etc.), the WG still suffers from a serious lack of manpower. Few colleagues outside the WG spontaneously send their orbits (though they are usually happy to send their data when we asked). Any help from authors, journal editors, etc., is therefore very welcome. Uploading an orbit into SB9 also means checking it against typographical errors. In this way we have found a number of mistakes in published solutions. Sending orbits to SB9 prior to publication (e.g., at the proof stage) would therefore be a way to prevent some mistakes from making their way into the literature.

Guillermo Torres
president of the Commission

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