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COMMISSION 30: Radial Velocities*

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Abstract. This report from Commission 30 covers the salient areas in which major progress has been made in the triennium covered by the present volume. The principal scientific areas are: The Milky Way, star clusters, spectroscopic binaries, extrasolar planets, pulsating stars and stellar oscillations. Following these, an account is given of the progress in techniques and methodology for radial velocity determinations. Finally, a summary is given of the progress made by the working groups of the Commission, followed by a list of key papers in the triennium. A more extensive report also covering extragalactic work, which due to unforeseen circumstances could not be included here, can be found at the web page of Commission 30 (`http://www.iau.org/IAU/Organization/divcom/`).

Keywords. Milky Way, spectroscopic binaries, pulsating stars, extrasolar planets, stellar dynamics, radial velocities

1. Introduction

Radial velocities – often called redshifts in extragalactic work – are key observational data in modern astrophysics. Applications range from the expansion of the Universe, the evolution of the Milky Way, and the search for extrasolar planets to seismological studies of the interior of the Sun. As diverse as these fields seem to be, they do in fact present many common threads in terms of instrumentation, data reduction techniques, and standardization of the results.

Accordingly, the first part of this report will give a brief overview of, first, the scientific fields where significant new results have been obtained in the last three years, starting with the Milky Way and its star clusters to double and single stars with and without planets. A section on extragalactic work was planned, but unexpected health problems prevented it from arriving in time; it can be found at the Commission web site listed above. The second part of the report covers the progress in methodology and archival of radial velocity observations and quantities derived from them. A list of references to key papers is given at the end.

2. Progress in Galactic structure

By B. Nordström

“The formation and evolution of galaxies is one of the great outstanding problems of astrophysics” (Freeman & Bland-Hawthorn 2002). That review on the Milky Way sets

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the scene for the triennium covered by this report. It is clear that for the future, wide-field all-sky surveys are needed, and complete and well-understood samples are of the utmost importance. Selection effects in previous data sets have severely hampered their interpretation.

In this section, we include some of the major advances and new data releases in stellar radial velocity work of importance for the understanding of the overall structure, formation and evolution of the Milky Way galaxy. The kinematics of the gas component is covered in reports from other commissions.

2.1. *Substructures in the outer galactic disk and halo*

Several surveys which include large numbers of stellar radial velocities have been published during the past three years. The main goal of the Sloan Digital Sky Survey (SDSS) is to obtain redshifts of 10^6 galaxies and 10^5 quasars, but it also includes a small percentage of stellar objects. This has lead to the release of about 80.000 stellar radial velocities, a significant number in comparison to what was previously available. Although the accuracy for each star is not high, the large number of stars in the outer disk and halo makes it possible to identify new structures (Newberg *et al.* 2002).

Following that first discovery, Yanny *et al.* (2003) find a ring of 500 stars at a distance of 5 kpc above the Galactic plane and 18 kpc from the Galactic centre. This is known as the “Monoceros ring” and has been confirmed by Conn *et al.* (2005) who observed radial velocities with the 2dF spectrograph at the Anglo Australian Telescope. The ring seems to be present on both sides of the Galactic plane.

An additional structure has been detected in Triangulum-Andromeda in the background of the Canis Major dwarf galaxy (Rocha-Pinto *et al.* 2004, Majewski *et al.* 2004b). These detections show the increasing complexity of structures which are revealed in large surveys of the outer Galactic disk and halo.

From several hundred radial velocities of M giants, Majewski *et al.* (2004a) find evidence for that some of the objects could be associated to the tidal tail system of the Sagittarius dwarf galaxy. Evidence for other velocity structures is found among the more distant (>13 kpc) M giants. Finally, a possible new dwarf galaxy in Ursa Major was announced by Willman *et al.* (2005a), who further discuss the nature of this overdensity of stars in Willman *et al.* (2005b).

2.2. *Halo and thick disk stars*

Allende Prieto *et al.* (2005) measured radial velocities for 22.770 F and G stars included in the third data release (DR3) of the SDSS. These stars are mainly from the thick disk and halo populations, and their metallicity and dynamical properties are discussed. New kinematical results of the Galactic halo from horizontal branch stars in the Hamburg/ESO survey were published by Thom *et al.* (2005)

2.3. *Thin disk stars*

The Geneva-Copenhagen Survey of the Solar Neighbourhood (Nordström *et al.* 2004) provides accurate, multiple radial velocities for a magnitude-complete, all-sky sample of 14,000 F and G dwarfs to $V = 8.5$ mag., and is volume complete to about 40 pc. The paper includes new mean radial velocities for 13,464 stars with typical mean errors of 0.25 kms^{-1}, based on 63,000 individual observations. This is the largest survey of accurate radial velocities of the triennium, based mostly on the photoelectric cross-correlation spectrometers CORAVEL and covering both hemispheres. Famaey *et al.* (2005) published CORAVEL radial velocities for 6,691 K and M giants in the northern sky.

Both surveys find dynamical substructures that are probably due to dynamical perturbations induced by spiral arms and perhaps the Galactic bar. These “dynamical streams” (Famaey *et al.* 2005) contain stars of different ages and metallicities and the stars do not seem to have a common origin. These features, which dominate the observed U, V, W diagrams, make the conventional two-Gaussian decomposition of the nearby stars into thin and thick disk members a highly dubious procedure. The data of Nordström *et al.* (2004) were analyzed by Helmi *et al.* (2005), who suggest that tidal debris from merged satellite galaxies may be found even in the solar neighbourhood.

Martin *et al.* (2005) observed 1500 red giant branch and red clump stars towards the centre of the Canis Major dwarf galaxy. These stars present a peculiar distance–radial velocity relation. The kinematical data can be reproduced in simulations of accretion of a dwarf galaxy on the Galactic disc.

2.4. *Hypervelocity star*

Brown *et al.* (2005) discovered a star, SDSS J090745.0+024507, which appears to be leaving the Galaxy with a heliocentric radial velocity of 853±12 kms^{-1}. They suggest that this is the first example of a hypervelocity star ejected from the Galactic centre.

3. Star clusters

By. E. Glushkova

In the last three years, progress in the spectroscopic studies of star clusters has occurred primarily in the study of extragalactic cluster systems. The availability of 8m- and 10m-class telescopes gives us the possibility to obtain spectra of individual clusters of sufficient quality to derive reliable kinematic and abundance information out to Virgo cluster distances. RVs of globular clusters have been measured in the giant elliptical galaxy NGC5128 (74 GCs)(Woodley *et al.* 2005), in M 49, the brightest member of the Virgo Cluster, (196 GCs) (Cote *et al.* 2003), in the dwarf irregular galaxies NGC 4214 and NGC 4449 and the spiral galaxy NGC 6946 (Larsen *et al.* 2004), and in M 83, NGC 1399, and NGC 524. Virial masses and mass-to-light ratios were estimated from velocity dispersions and photometry. The kinematics of the metal-rich and metal-poor clusters were studied separately and showed different features. The dynamical mass of the most luminous stellar cluster W3 in the merger remnant galaxy NGC 7252 has been estimated from the velocity dispersion to be $8 \pm 2 \times 10^7$ $\mathrm{M}_\odot$, a result which poses questions about the nature of this object (Maraston *et al.* 2004).

Interesting results were also obtained for Milky Way globular clusters. Radial velocities of 1589 members of ω Cen were measured by the ARGUS spectrometer at the CTIO 4m telescope and were combined with internal proper motions to construct a detailed dynamical model of the cluster and find its dynamical distance (4.8 ± 0.3 kpc) (Reijns *et al.* 2005, van de Ven *et al.* 2005). Infrared velocity curves for 12 variables in 47 Tuc were obtained by Lebzelter *et al.* (2005c). Radial and rotation velocities from UVES+VLT of 61 stars in the GCs NGC 1904 (M 79), NGC 2808, NGC 6093 (M 80) and NGC 7078 (M 15) were measured by Recio-Blanco *et al.* (2004).

Ongoing comprehensive radial velocity surveys of open clusters are part of the WIYN Open Cluster Study. During the triennium, the following clusters were studied in the frame of this survey: NGC 6819, NGC 2168 (M 35), NGC 188, NGC 2264, NGC 6475 (M 7), and the Pleiades (Meibom *et al.* 2003, Angle & Pilachowski 2005, James *et al.* 2004, Margheim *et al.* 2003). In the first three clusters, large samples of binaries were found, and their orbits were used to derive the tidal circularisation cutoff period (the transition between eccentric and circular orbits). Radial velocities of individual members and the mean RVs were measured in open clusters Be 20, Be 21, NGC 2141, Be 29, Be 31, IC 2488, NGC 1817, NGC 2477, NGC 3293, NGC 4755, NGC 6611.

The internal kinematics of young cluster NGC 6913 was studied and its dynamical mass estimated from the radial velocity dispersion (Boeche *et al.* 2004). Rotational velocities and radial velocity dispersion were measured for very young stars in Orion Nebular cluster (Sicilia-Aguilar *et al.* 2005); and RVs for 8 stars in the region of the Galactic OB association Bochum 7 were also obtained.

Radial velocities were measured to confirm the membership of X-ray selected stars in the open clusters NGC 2451 A and B, and in Be 29, the farthest cluster known in our Galaxy. Confirmed red giant stars were used to estimate the distance to Be 29 of 15 kpc and its metallicity [Fe/H]=- 0.74 ± 0.18 (Bragaglia *et al.* 2005) Combining precise BV photometry and radial velocities, a firm orbital solution for the newly discovered eclipsing binary HD 23642 in the Pleiades was calculated. The resulting distance to the binary and, therefore, to the cluster is 132 ± 2 pc (Munari *et al.* 2004).

4. Spectroscopic binaries

By G. Torres

More than 3,000 spectroscopic binaries were identified in the Geneva-Copenhagen Survey of the Solar Neighbourhood (Nordström *et al.* 2004), described earlier. This presents a rich source of new binary and multiple objects for further study.

675 possible new binaries were identified by Pourbaix *et al.* (2005) in the spectroscopic observations taken as part of the Sloan Digital Sky Survey, and orbits were presented for 8 of them. Results published for other samples of stars include 14 binaries with spectroscopic orbits among metal-poor red giant and horizontal-branch stars in the field (Carney *et al.* 2003), 18 orbits for Am stars (Carquillat *et al.* 2003, Carquillat *et al.* 2004), 81 orbits for stars in the field of the open cluster M35 (Meibom & Mathieu 2005) (32 of which are confirmed members), 30 orbits for close systems from the program led by S. Rucinski (Rucinski *et al.* 2003, Pych *et al.* 2004, Rucinski *et al.* 2005), and of course the continuing series of papers by R. Griffin in The Observatory, reporting some 4 dozen spectroscopic orbits over the period of this report. Spectroscopic observations in the infrared for other objects have allowed the detection of faint secondaries in some cases, converting single-lined binaries into double-lined binaries (e.g. Mazeh *et al.* 2003, Simon & Prato 2004) and yielding more information on the masses.

A number of studies of the statistical properties of spectroscopic binaries have appeared in the last 3 years. The mass ratio distribution was investigated by Goldberg, Mazeh & Latham (2003) and Fisher, Schröder & Smith (2005), and a new measure of tidal circularization in coeval binary populations was introduced by Meibom & Mathieu (2005). The widely used criterion of Lucy & Sweeney 1971 for assessing the reality of small eccentricities in spectroscopic orbits has been extended by Lucy (2005).

An important by-product of the searches for transiting extrasolar planets has been the discovery that several of the companions are very low-mass stars, which produce similar photometric signatures as true planets. The determination of their spectroscopic orbits, along with the fact that they are eclipsing, has allowed the measurement of rather precise masses and radii for these objects (Bouchy *et al.* 2005, Pont *et al.* 2005a), which are of considerable interest for testing models of stellar structure and stellar evolution in the lower main-sequence. In particular, they provide useful constraints on the mass-radius relation. One of these objects, OGLE-TR-122, is the lowest mass star to date with a direct radius determination ($M = 0.085 \pm 0.008$ $\mathrm{M}_\odot$, $R = 0.114 \pm 0.009$ $\mathrm{R}_\odot$ Pont *et al.* 2005b).

5. Extrasolar planets

By S. Udry

The period covered by this report has seen tremendous developments in the exoplanet domain. We emphasize here the major results of the past 3 years, mainly focusing on those related to the radial-velocity technique.

5.1. *Statistical properties of exoplanets*

First, the number of known planets is rapidly rising (more than 50% increase since the last report). It is now over 160, mostly resulting from the increase in the baseline of the radial-velocity data and the launch of new large surveys as e.g. the HARPS planet search (Mayor *et al.* 2003) or metallicity-biased searches for Hot Jupiters (e.g. Fischer *et al.* 2005). The planet list has grown to a number giving some confidence in the observational constraints drawn from the observed statistical distributions of the planet properties (see e.g. Marcy *et al.* 2002 and Udry *et al.* 2003). Detailed discussions on the different properties may also be found in the proceedings of the conferences in Paris (*Extrasolar Planets: Today and Tomorrow,* 2003, ASP Conf. Ser. 321), Aspen (*Planet Detection and Formation,* February 2005) and OHP (*10th Anniversary of 51 Peg b,* August 2005).

The variety of planetary characteristics is gradually growing. We have long-period candidates (more than 10 years), a mass range that goes from below the mass of Neptune (Santos *et al.* 2004, McArthur *et al.* 2004) up to masses above 15 $\mathrm{M}_{\mathrm{Jup}}$, and candidates on circular orbits as well as with very high eccentricities. In some systems, long-period planets resemble our giant planets of the Solar System (Naef *et al.* 2003, Marcy *et al.* 2002).

The study of the orbital period distribution has shown that migration processes might explain the observed current configuration of the planetary systems (piling-up of planets with periods around 2-3 days, rise of the number of massive planets with distance (e.g. Udry *et al.* 2003 and references therein). Also a paucity of high-mass companions orbiting in short period trajectories has been pointed out.

A newly developing area of exoplanet properties relies on the existence of planets in wide and spectroscopic binaries. They seem to have orbital properties different from planets around “single” stars. Moreover, short-period massive planets seem to be more frequent around stars in binary systems than around single stars (Zucker & Mazeh 2002).

The number of multi-planetary systems is rising as well, to 19 today. Several of those systems are found in resonant configurations like e.g. period ratios of 2:1 for three of them (e.g. Mayor *et al.* 2004, Laughlin *et al.* 2005). In such configurations, planet-planet interactions bring further information on the orbital inclinations of the system.

5.2. *From hot Jupiters to hot Neptunes and below*

With the recent detection of several planets in the Neptune-mass regime (McArthur *et al.* 2004, Santos *et al.* 2004, Butler *et al.* 2004, Vogt *et al.* 2005), another milestone was reached. A step forward on the instrumentation side was taken with the development of a new generation of instruments capable of radial-velocity measurements of unprecedented quality. The pioneer among them is undoubtedly the ESO high-resolution HARPS fiber-fed echelle spectrograph especially designed for planet-search programmes and asteroseismology. Its vacuum enclosure eliminates the disturbing effects of the varying atmospheric pressure, and it reaches an instrumental radial-velocity accuracy at the level of $1\,\mathrm{m\,s^{-1}}$ over months/years (Mayor *et al.* 2003, Lovis *et al.* 2005), and even better on a short term basis (Bouchy *et al.* 2005a). Another fundamental change that has allowed this progress in planet detection towards the very low masses is the application of a careful observing strategy to minimize the perturbing effect of stellar oscillations, which may hide the tiny radial-velocity signal induced on solar-type stars by Neptune-mass planets.

The planet mass distribution, which was known to be heavily biased against low masses, can now be explored in greater detail. The characterization of the low-mass objects will strongly constrain planet formation and evolution scenarios, as planets with masses between 10 and $100\,M_\oplus$ are not expected in large numbers according to some current formation models (e.g. Ida & Lin 2004).

5.3. *Transiting exoplanets and radial-velocity follow-up*

The *radial-velocity method* is still the more efficient way to search for exoplanets. However, wide-field photometry is now also giving important results. Photometric observations of a giant-planet transit in front of its parent star provide independent confirmation of the nature of the companion and yield the true mass, radius, and mean density of the planet when combined with radial-velocity measurements.

The OGLE III project has announced more than 170 small-size transiting objects (Udalski *et al.* 2003, Udalski *et al.* 2004). Five of them have been confirmed as planets by radial-velocity follow-up (Bouchy *et al.* 2004, Pont *et al.* 2004, Bouchy *et al.* 2005, Konacki 2005). The OGLE stars are faint (V=15-17), which limits the possibilities for complementary observations. Joining the early discovery HD209458b, a brighter candidate, TrES-1, was detected from photometry and confirmed through RV measurements by Alonso *et al.* (2004). 2 more transiting planets were announced from metallicity-biased RV programmes, HD149026 (Sato *et al.* 2005b) and HD189733 (Bouchy *et al.* 2005b), and then confirmed through photometric follow-up. They provide ideal targets for further investigation, like the detection of thermal emission from the planet (Charbonneau *et al.* 2005).

Transiting companions are starting to populate the mass-radius relation for planets providing strong constraints for planet-interior models (Bouchy *et al.* 2004, Pont *et al.* 2005a). An interesting but intriguing linear relation between the period and mass of transiting planets was pointed out by Mazeh *et al.* (2005).

5.4. *Parent star properties*

Further information to constrain planet formation models come from the study of the planet hosts themselves. The observed relation between the frequency of planet detection and the metallicity of the parent star is further confirmed (Santos *et al.* 2005, Fischer & Valenti 2005). These authors have also shown that the probability of hosting a giant planet is a strongly rising function of the metal content of the star. According to their estimate, up to 25 - 30% of the more metal-rich stars ($[\mathrm{Fe/H}] > 0.2$ - 0.3) can be expected to host a giant planet.

The mass of the primary star is also an important parameter for planet formation processes. Giant planets seem to be rare around M dwarfs, although this result still suffers from small number statistics. On the contrary, 3 among the 5 planets found to orbit an M dwarf have masses below $21\,M_\oplus$ and are probably "solid" planets. For more massive primaries, new surveys targeting earlier-type, rotating A-F dwarfs and programmes surveying G-K giant stars are starting to provide interesting planetary candidates (Setiawan *et al.* 2005, Sato *et al.* 2005b, Hatzes *et al.* 2005). The detected planets are massive, but it is still too early to conclude whether a "primary-mass" effect exists, as those programmes are still strongly observationally biased.

5.5. *Conclusion and prospects*

An important lesson from the past few years is that the radial-velocity technique has not reached yet its limits in the domain of exoplanet searches.

As described above, radial-velocity follow-up measurements are mandatory in order to derive the mass and mean densities of the transiting companions. They so confirm the planetary nature of the companions and provide important parameters to constrain planetary atmosphere and interior models. This is important in view of the expected results of the space missions CoRoT and Kepler, which should provide hundreds of transit candidates of various sizes and masses, in the coming years.

Also, results obtained with the HARPS spectrograph show that, even if stars are intrinsically variable in radial velocity (at different levels) due to acoustic modes or stellar activity, it is nevertheless possible to reach precisions well below $1\,\mathrm{ms}^{-1}$ ($10\,\mathrm{cms}^{-1}$) by applying an adequate observational strategy on well selected *quiet* stars. Thus, as long as we accept to pay the price in terms of telescope time, radial-velocity measurements on specially designed spectrograph (advanced temperature and pressure control) should in principle be able to detect Earth-type planets (Pepe *et al.* 2005).

6. Pulsating stars and stellar oscillations

By L. Szabados

The new possibilities for obtaining precise stellar radial velocities have stimulated a large number of asteroseismologic studies. Many papers based on the analysis of RV data were published in the last triennium. The following list is only a selection of the most important results based on RV data.

6.1. *Beta Cephei type variables*

Neiner *et al.* (2003b) identified both radial and nonradial pulsation modes in V2052 Ophiuchi. Aerts *et al.* (2003) found seven independent pulsation frequencies in ν Eridani from the data collected during a multisite spectroscopic campaign. At least five pulsation modes have been detected in ϵ Centauri (Schrijvers *et al.* 2004).

6.2. *Other B type variables*

Rapid line-profile variability of the Be star ω Canis Majoris was explained in terms of interactions between the disk and the photospheric non-radial pulsation (Stefl *et al.* 2003). Possible non-radial pulsations have been detected in the known Be star HP Canis Majoris by Carrier & Burki (2003b). Rapid multi-mode pulsations have been detected in Przybylski's star (=V816 Cen) (Mkrtichian & Hatzes 2004). ζ Cassiopeiae was found to be a non-radial pulsator (slowly pulsating B star) by Neiner *et al.* (2003a) The subdwarf B star PG 1325+101 was found to be a pulsating variable (Telting & Ostensen 2004). The most likely reason for the short time-scale variability in central stars of young planetary nebulae (archetype ZZ Leporis) is stellar pulsation (Handler 2003).

6.3. *Rapidly oscillating Ap stars*

Kochukhov (Kochukhov 2004a, Kochukhov 2004b, Kochukhov 2005) developed a numerical technique for analyzing the line profile moment variations for Ap stars. This method was applied to IM Velorum by Kochukhov *et al.* (2004c). The radial velocities of α Circinis are modulated by a short period oscillation, possibly a low amplitude Delta Scuti pulsation (Balona & Laney 2003). Mkrtichian *et al.* (2003) performed a detailed study of the roAp star GZ Librae. Precise RV time series of β Coronae Borealis indicate this star to be a new roAp star pulsating with a period of 16.21 min and amplitude of 0.14 $\mathrm{km s^{-1}}$ (Hatzes & Mkrtichian 2004). Another newly discovered roAp star is HD 116114, with a pulsation period of 21 min and highest RV amplitudes of about 0.1 $\mathrm{km s^{-1}}$ (Elkin *et al.* 2005a). Lack of pulsation in the Ap star HD 965 is due to the geometrical structure of the magnetic field (Elkin *et al.* 2005b). Mkrtichian & Hatzes (2005) carried out a detailed analysis of the pulsation modes, their amplitudes and phases for DO Eridani. For another roAp star, V1286 Aquilae, they found that pulsational radial velocity variations are only present in 5 spectral lines (Hatzes & Mkrtichian 2005).

6.4. *Delta Scuti and related stars*

The solitary Am star HD 8801 is a new pulsating star performing both γ Dor and δ Scuti type oscillations (Henry & Fekel 2005). Henry *et al.* (2005) found 11 new γ Dor type stars partly from RV data. The primary component of the spectroscopic binary HD 104237 is a known pulsating variable (DX Cha). Böhm *et al.* (2004) pointed out these Delta Scuti type oscillations from the RV data, and this is the first when such oscillations in a pre-main sequence star are found by spectroscopic means.

6.5. *Classical pulsators (Cepheids, RR Lyrae type variables)*

The database of Fourier coefficients of decomposed radial velocity (and light) curves of Cepheids and RR Lyrae stars is maintained and described by Morgan (2003). Synthetic RV curves for Cepheids have been calculated from new pulsation models by Petroni *et al.* (2003) and Ruoppo *et al.* (2004). Biazzo *et al.* (2004) elaborated a method for measuring simultaneously the temperature and radial velocity of Cepheids from line-depth ratio. A new modelling and discussion of the projection factor for converting the pulsation velocity into RV is published by Nardetto *et al.* (2004).

6.6. *Luminous red pulsators*

The extended and velocity stratified dynamic atmosphere of the hypergiant ρ Cassiopeiae was studied during an outburst by Lobel *et al.* (2003). Two main periods (366 and 186 d) due to pulsation were found as a result of long term RV monitoring of the C-rich semi-regular variable WZ Cassiopeiae (Lebzelter *et al.* 2005a). The 3D kinematics of the water masers around the SR variable RT Virginis was studied by Imai *et al.* (2003), while Nowotny *et al.* (2005) studied the atmospheric dynamics in carbon-rich Miras. Bright southern LPVs exhibiting various anomalies were studied by Lebzelter *et al.* (2005b). Long secondary periods are frequently found at the pulsating AGB stars. These long periods revealed from both radial velocity and photometric observations may be caused by low degree g^{+} mode oscillation (Olivier & Wood 2003, Wood *et al.* 2004).

6.7. *Pulsating stars in binary systems*

The Beta Cephei type pulsating component in the triple system of λ Scorpii was studied based on 815 spectra covering a timespan of 14 years by Uytterhoeven *et al.* (2004). Orbital elements and non-radial pulsation modes have been determined for the binary system κ Scorpii and its BCEP component (Harmanec *et al.* 2004). For another system with BCEP component, V381 Carinae, the influence of the pulsational line-profile variations on the radial velocities was eliminated in order to determine the orbital elements of the binary system (Freyhammer *et al.* 2005). For the single-lined SB α Draconis, whose primary is a suspected Mira type variable star, Kallinger *et al.* (2004) pointed out very small (40 ms^{-1} in RV) amplitude oscillations with a period of 53 min.

Lehmann & Mkrtichian (2004) found multiperiodic oscillations with two dominant frequencies from RV data in the Algol type EB RZ Cas. Spectroscopic orbits has been determined for the Cepheids Y Carinae, YZ Carinae, AX Circinis, BP Circinis, V636 Scorpii, W Sagittarii, and T Monocerotis – all are members of binaries – properly separating the RV variations due to pulsation (Petterson *et al.* 2004). An online database on Cepheids belonging to binary systems has been maintained and described by Szabados (2003). Pulsations of the cool component of the symbiotic binary AG Draconis have been found from the existing RV data (Friedjung *et al.* 2003).

6.8. *Solar-type oscillations*

Bertaux *et al.* (2003) analyzed the stellar oscillations from RV time series in ζ Her obtained by correlating the signals observed simultaneously with two different instruments. 12 modes were identified in the oscillations of α Cen B. The mean noise level in the amplitude spectrum obtained from the CORALIE data is 3.75 cms^{-1} (Carrier & Bourban 2003a). For η Bootis, Kjeldsen *et al.* (2003)) identified 21 modes, While Carrier *et al.* (2005a) found 22 individual modes from the RV data. Procyon A was investigated further; the three major published analyses are those by Martic *et al.* (2004), Eggenberger *et al.* (2004), and Claudi *et al.* (2005). In β Virginis, 21 individual modes have been identified (Carrier *et al.* 2005b).

6.9. *Miscellaneous*

Lada (Lada *et al.* (2003)) performed high resolution molecular-line observations of the dark nebula Barnard 68 with the IRAM 30m telescope. The spatial pattern of the velocity field indicates non-radial oscillations of the outer layers of the cloud.

7. The stringent definition of “radial velocity”

By D. Dravins

Very high measuring precisions, differential lineshifts measured in the same star, and astrometric determinations of radial motion have required the concept of “radial velocity” to be more stringently defined, in order to permit comparisons between various measurements on accuracy levels of ms^{-1}. Relativistic effects, measurements being made inside gravitational fields, and alternative choices of coordinate frames, cause the naive concept of radial velocity being equal to the time derivative of distance, to become ambiguous at accuracy levels around 100 ms^{-1}.

Two resolutions for the stringent definition of spectroscopic and astrometric radial velocities were adopted at the IAU XXIVth General Assembly in Manchester. The resolution texts are published in IAU Inf. Bull. 91, 50 (2002), while their implications were discussed by Lindegren & Dravins (2003). Those definitions were referred to an observer within the solar system, and include the definition of a “barycentric radial-velocity measure” as the result of a spectroscopic measurement.

Recent work elsewhere has applied general relativity with an aim of making the definition even broader, e.g., not requiring the observer to be within the solar system (Bolos 2005 and Manoff 2005).

8. Radial velocity precision

By G. Torres

The trend toward increasingly precise radial velocity determinations for stars has continued during this period, driven largely by Doppler searches for extrasolar planets. Two main techniques have yielded the best results so far. In one, starlight passes through an iodine gas absorption cell (e.g. Butler *et al.* 1996), which imprints a rich forest of I_2 lines on the stellar spectrum; these allow to track even the smallest of instrumental shifts. The simultaneous Thorium-Argon technique (Baranne *et al.* 1996) relies instead on the exposure of a Th-Ar lamp during the integration on the star, with the star and the lamp fed to the spectrograph through separate optical fibers, to much the same effect as the I_2 method.

These techniques have matured to the point where single measurements now yield precisions under 10 ms^{-1} quite routinely over long timescales, as needed to detect planets. Whereas 5–10 years ago this was largely the exclusive domain of the two planet search groups who pioneered these techniques (the California-Carnegie team and the Geneva team, respectively), the last few years have seen the same capabilities extended to other facilities and groups. In addition to the improvements on the hardware side, advances in reduction and analysis techniques have made a significant difference as well, and a number of projects now report precisions approaching 3 ms^{-1} (Cochran *et al.* 2004, Endl *et al.* 2004, Marcy *et al.* 2005, Tinney *et al.* 2005, Sato *et al.* 2005a), at least for relatively bright stars ($V < 11$).

Even higher precisions of 1 ms^{-1} have been reached with the commissioning by the Geneva group in 2003 of the HARPS instrument on the 3.6-m ESO telescope at La Silla, designed specifically for planet searches and asteroseismology e.g. (Lovis *et al.* 2005). The extremely high stability of the spectrograph, which is mounted in a temperature-controlled vacuum tank, allows this accuracy to be maintained over periods of years.

The push for better velocity precision has also reached fainter stars, and several teams have achieved 50–100 ms^{-1} errors for sharp-lined stars as faint as $V = 17$ (e.g., Bouchy *et al.* 2005a, Konacki *et al.* 2005), in the context of follow-up observations of candidate extrasolar transiting planets from the OGLE survey.

Applications of these advances in velocity precision have also been made in the field of stellar astronomy. Delfosse *et al.* (2004) report on a large program to search for and characterize M dwarf binaries with the ELODIE spectrograph on the 1.93-m telescope at the Observatoire of Haute Provence (France), reaching precisions as high as 15 ms^{-1} for $V < 11$. Results from a variability study among G and K giants with the FEROS instrument on the 1.52-m ESO telescope at La Silla were published by Setiawan *et al.* (2004), who report precisions of about 25 ms^{-1} over a 2.5-year period. Both of these studies used the simultaneous Th-Ar technique.

Similar results have also been obtained by more classical techniques by Skuljan, Ramm & Hearnshaw (2004), who used a highly stable fiber-fed spectrograph on the 1-m telescope at Mt. John University Observatory (New Zealand). Their velocity measurements with a precision of 14 ms^{-1} allowed them to obtain very accurate orbital parameters for the 13-day period binary star ζ TrA, including a very small but highly significant eccentricity.

While the iodine technique has until recently only been applied to single-lined spectra in the context of planet searches, Konacki (2005) introduced a new procedure that allows it to be used for composite spectra. Velocity precisions of 20–30 ms^{-1} are possible for stars of spectral type F3–F8 in double-lined systems, and 10 ms^{-1} for later type stars.

9. Working groups

9.1. *Bibliography of stellar radial velocities*

By H. Levato

Members of the working group: H. Levato (chair) and S. Malaroda, with technical support from S. Galliani.

The WG has updated the Bibliographic Catalogue of Radial Velocities during this period at a rate of a new update each semester. At the time of this writing the update up to June 30 2005 (version 2005.5) has been published and version 2006.0 will be available before the Prague GA at the WEB site `http://www.casleo.gov.ar` and at the CDS.

The last published version 2005.5 has 73,449 entries, more than a factor of three increase in the last 9 years. Thirty two journals are continuously scanned for stellar radial velocity measurements.

The user may find at the web page where the catalogue is located, a search facility for searching directly by star number or through a coordinate range. We will improve soon the searching possibilities.

9.2. *Radial-Velocity standard stars*

An updated summary will be published by S. Udry at the web page of Com 30 (see `http://www.iau.org/IAU/Organization/divcom/`)

9.3. *Orbital elements of spectroscopic binary systems*

By D. Pourbaix (chair), A.H. Batten, F.C. Fekel, W.I. Hartkopf, H. Levato, N.I. Morell, A.A. Tokovinin, G. Torres, and S. Udry

At the IAU GA 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 Summer 2001 and the paper by Pourbaix *et al.* (2004) was published in A& A. Several investigations are already taking advantage of this database.

Thanks to W. Hartkopf and B. Mason, there is now a link to SB9 from the Commission 26 web page. There is also a collaboration with E. Oblak (Besancon) and his double star database. The latter interrogates SB9 whenever the object is known to be present in our DB. A similar collaboration also exists with the CDS thanks to F. Ochsenbein.

For the time being, SB9 contains 2472 systems (1469 in SB8) and 2898 orbits (1469 in SB8). A total of 461 papers were added since August 2000. We still have a list of 459 identified papers for which orbits need to be typed in.

Even though this work is very welcome by the community and some tools have been designed to make the job of entering new orbits easier (input file checker, plot generator, ...), the WG still suffers a serious lack of manpower. Few colleagues outside the WG spontaneously send their orbits (but they are usually pleased to send their data when we ask for them). Any help (from authors, journal editors, ...) is therefore very welcome.

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