Complementary Approaches to Double and Multiple Star Research, IAU Colloquium 135, ASP Conference Series, Vol. 32, 1992
Harold A. McAlister and William I. Hartkopf (eds.)

Precise Radial Velocities

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ABSTRACT: Current techniques for the detection of long-term, low-amplitude (<50 m s^{-1}), radial velocity variations are briefly reviewed together with some of their most successful programs. In the era of 8- to 10-m telescopes we must strive for a precision of < 1 m s^{-1}.

1. INTRODUCTION

The radial velocity of any astronomical object is of fundamental interest. With a long–term precision of better than 1 m s^{-1} we could look for such basic phenomena as stellar acoustic oscillations, perturbations by systems of planets, and secular acceleration. In theory, the accuracy with which one can estimate the position of a stellar spectral feature on a multi-channel detector is limited ultimately by signal to noise. The real challenge is to reliably calibrate that position as a wavelength or change of wavelength over many years. For a spectrograph with a resolution R ~50,000, 1 m s^{-1} corresponds to $\sim 10^{-4}$ of the detector pixel width, or about 10^{-3} μm! While displacements caused by spectrograph seeing, dimensional stability of the spectrograph, collimation errors, etc. , are orders of magnitude larger.

At the moment, several groups regularly achieve a precision of ~10 m s^{-1}. For nearby solar–type stars, this has been sufficient to eliminate the presence of Brown Dwarf companions (with P <50 yr) and to set limits for single, massive planets as secondaries. In has also revealed that yellow giants, once taken as reliable velocity standards, are low–amplitude velocity variables with a wide range of periodicity. In all but one of these techniques, systematic errors introduced by spectrograph instability and decollimation are eliminated by directly imposing in the stellar spectra, artificial or natural, wavelength fiducials in absorption, or transmission. To achieve this, one requires a critically controlled interferometer or a captive gas. While many people have demonstrated the effectiveness of telluric lines as fiducials, they are less satisfactory than a captive gas and I am not aware of any long–term programs to exploit them.

2. PRV TECHNIQUES

With the emphasis in this colloquium on multiple stars, I shall focus on those techniques (as far as I am aware) which regularly achieve a long–term stability of <50 m s^{-1} rms. For the highest internal precision, spectral features must be resolved and as many stellar features as possible measured simultaneously.

[1]**This paper was read in Dr. Walker's absence by Dr. David Latham.**

2.1. Fibre–Fed/Conventional

Brown & Gilliland (1990) have shown that a fibre–fed spectrograph can be used with short exposures on a bright enough star to look for the spectrum of acoustic oscillations from solar–type stars.

On the longer term, Murdoch & Hearnshaw (1991) have nicely demonstrated how many of the factors which normally limit precision (e.g., guiding and flexure) are minimised by the scrambling action of the fibre. They feed an échelle spectrograph thermally isolated in a room next to the dome with a single fibre from the Mt. John University Observatory McLellan 1-m Cassegrain telescope. Spectra of a Th-Ar hollow cathode lamp (at the telescope end of the fibre) taken before and after each exposure gives them an averaged dispersion solution. The detector, an 1872 Reticon, covers some 45 Å ($\sim$ 30 strong stellar features) centred at 5010 Å at a dispersion of 1.75 Å mm^{-1}.

They derive differential radial velocities by cross–correlation using an earlier spectrum of the target star as template. They estimate a systematic correction for each run from the average differential radial velocity of 14 program stars which seem constant in velocity.

As one would expect, the errors in this technique increase with exposure time. From observations over 2.5 years the very bright star α Cen A (exposure $\sim$ 2 min) give an external rms error of 37 m s^{-1} with errors within a run being about 15 m s^{-1}. For stars with $V = 3$ the external rms error is 50 m s^{-1}, for $V = 4$, 65 m s^{-1}, $V = 5$, 90 m s^{-1}. Their careful work probably represents the limiting precision for such a classical technique.

It is worth remembering that currently, in all cases, a fibre–feed introduces a transmission loss of nearly a magnitude.

2.2. Potassium Magneto–Optical Filter

Isaak and his group at the University of Birmingham have developed a magneto–optical filter spectrometer (see Innis *et al.* 1991) having atomic potassium vapour as the local wavelength standard for the 7699 Å D_1 stellar potassium feature. The filter has two 30 mÅ passbands symmetrically placed about the rest wavelength of the potassium line and separated by around 10 km s^{-1}. Only when the star's topocentric velocity is within some 5 km s^{-1} of zero are the passbands on opposite sides of the stellar line and the relative intensities give a measure of the radial velocity of the star. They use a null method to measure radial velocity absolutely. It is applicable only for stars of low heliocentric velocity, near the ecliptic plane. They argue that at the instant when the intensities in the two passbands are equal, the topocentric velocity of the star must be zero. Since the Earth's motion can be calculated to high accuracy (using the JPL ephemeris), the reflex corresponds to the star's barycentric radial velocity.

Apart from the strict limitation to observations of solar–type stars with topocentric velocities which pass through zero, and to those few nights each year when it is zero, the filter transmission is low ($< 1\%$) which, coupled with the narrow bandpass and restriction to the single line of potassium they achieve a standard deviation of 200 m s^{-1} in 8 s on Procyon with the 1.9 m telescope at Mt. Stromlo and $\sim$3 m s^{-1} in 8 hours. With the barycentric velocity changing by as much as 2 m s^{-1} minute^{-1} their poor short–term precision must limit their ability to determine the time of zero crossing with good precision. At this time

https://doi.org/10.1017/S025292110000614X Published online by Cambridge University Press

there is no satisfactory estimate of long–term errors. From their better quality data obtained on Procyon A in 1989, 1990, and 1991 Innis quotes an agreement between velocities on successive nights of 7, 35, and 8 m s^{-1}.

2.3. Fabry–Perot Calibrated Spectrometer

Since 1985 McMillan *et al.* (1990) have regularly used the 0.9-m telescope of the Steward Observatory (University of Arizona) on Kitt Peak to fibre–feed an échelle spectrometer which has a tilt–tunable Fabry–Perot (FP) in the collimated beam. The FP introduces 0.05 Å wide transmission fringes on a 0.64 Å pitch in the stellar spectrum. The FP is tilt–tuned for each star such that certain fringes symmetrically scan particular lines in the stellar spectrum. The échelle is crossed with a plane grating, and ten orders corresponding to the spectral region 4250–4750 Å and 300 fringes are recorded with a CCD. Spectral resolution and absolute wavelengths of the transmission fringes depend entirely on the FP etalon which is calibrated approximately 100 times a night with a single Ar II arc line at 4278.7319 Å.

External standard deviations of between 20 and 40 m s^{-1} are quoted for program stars with the standard error for each season being typically $\sim$ 10 m s^{-1}. Long–term systematic errors are calibrated by observing sunlight scattered from the lunar crater Mosting A. The overall standard deviation from 466 observations is 8 m s^{-1} while the standard deviation of a quick series of observations of the crater on one night was 5 m s^{-1}. Given an external interferometer calibration error of 5 m s^{-1}, this leaves little room for variations in the Sun!

2.4. Iodine Vapour

Two groups, Marcy & Butler (1992) using the Lick 3-m coudé auxiliary telescopes, and Cochran & Hatzes (1990) using the McDonald 2.7-m telescope, impose the molecular iodine (I_2) spectrum as wavelength fiducial by passing the starlight through an absorption cell (5 cm diameter by 10 to 15 cm long) prior to the spectrograph slit. The vapour is at approximately 10^{-2} atm and the cell is maintained at 50 $\pm$0.1 C to ensure that all of the iodine is in the vapour phase. The spectrum is dense with some two or features per Å.

Marcy & Butler acquire about 30 orders in the Hamilton échelle spectrograph with a 2048$\times$2048 CCD which covers the I_2 spectrum between 5000 and 6300 Å. The resolution is 40,000. They use an over–sized mask on the collimator to avoid the effect of decollimation errors. From the reduction of six spectral orders containing some 30 stellar and a few hundred iodine absorption lines they find a long–term precision of $\sim$25 m s^{-1}. The iodine lines are intrinsically too sharp for adequate sampling at R=40,000, and the effects of blends and aliasing could be setting a limit to their precision.

Cochran & Hatzes, on the other hand, acquire 11.6 Å centered on 6300 Å (covering some 10 stellar features) in a conventional coudé spectrograph with an 800$\times$800 CCD at a resolution of 180,000. From repeated observations of the Moon they conclude that their long–term stability is better than 10 m s^{-1}, possibly 6 m s^{-1}.

As with all of the captive gas techniques, a program star is normally observed through the gas with occasional spectra being taken with the cell removed. The iodine–free spectrum, after appropriate displacement and stretching, is used

https://doi.org/10.1017/S025292110000614X Published online by Cambridge University Press

to give the iodine spectrum freed from the stellar spectrum leading to the accurate dispersion curve which is the basis of the precise wavelength determination.

2.5. Hydrogen Fluoride

The group centered at UBC and U. Victoria uses the 3–0 vibration–rotation band of HF near 8700 Å as fiducials (see Campbell & Walker 1979). To avoid polymerisation the gas is kept at 100 C at a pressure of 0.36 Torr in a 90 cm long cell. Unlike the crowded I_2 spectrum the HF produces a comb of 7 or 8 lines at roughly 10 Å intervals. The lines are intrinsically broad and readily resolved at their resolution of 40,000. The detector is an RL 1872F/30 EG&G Reticon which covers some 16 useful stellar features. Campbell, Walker, Yang, Irwin and others have had long-term programs underway for more than a decade using the identical coudé spectrographs on the CFHT 3.6 m and DAO 1.2 m telescopes. We quote a mean external error over this period of 13 m s^{-1} (see Campbell *et al.* 1988).

The technique has both high slit transmission and high photometric fidelity through use of a Richardson image (pupil) slicer. On the other hand, 8700 Å coincides with an absorption band of metallic aluminum so that system through–put is significantly reduced at every aluminum reflection. Also, handling HF is not for the faint hearted!

At $R = 40{,}000$, stellar lines are barely resolved for slow rotators and, as with both of the groups working with iodine, the form of the instrumental profile (*lsf*) and the systematic effects introduced by convolving it with different intrinsic line widths is a critical problem for long–term precision since the *lsf* almost certainly changes from run to run. Currently, we apply run corrections based on the average trend of all program stars observed in that run. In our view, the pupil–slicing action of the image–slicer and adjustment of the 4–grating mosaic are the most serious contributors to the run corrections.

3. IMPORTANT PRV RESULTS

3.1. Brown Dwarfs

All of the long–term PRV programs have been directed to solar or later–type stars. Marcy & Moore (1989) and Marcy & Benitz (1989) monitored 65 stars, most of them M dwarfs, the UBC and U. Victoria groups continue to monitor 23 solar–type stars, and Murdoch & Hearnshaw (1991) have monitored 29 solar–type dwarfs. While between them they have turned up a number of previously unsuspected spectroscopic binaries, for periods less than 50 years, none of the secondaries is in the Brown Dwarf range 0.01 to 0.08 $\mathcal{M}_\odot$ except, conceivably, the companion to HD 114762 (see Cochran *et al.* 1991, Latham *et al.* 1989).

3.2. Velocity Variability of Yellow Giants

Long thought to be stable and suitable as IAU velocity standards, the yellow (K and early M) giants have proved to be intriguing low–amplitude velocity variables with periods from days to years being present in each star (see Smith *et al.* 1987, Cochran 1988, Innis & Isaak 1988, Irwin *et al.* 1989, Walker *et*

https://doi.org/10.1017/S025292110000614X Published online by Cambridge University Press

al. 1989, Murdoch *et al.* 1992). The level of variability appears to be related to the degree of chromospheric activity.

3.3. Constant Integrated Velocity of the Sun

McMillan monitored the Moon from 1987 April through 1992 February. Despite the daily sunspot counts increasing from close to solar minimum to well past the maximum activity of Cycle 22, the integrated velocity of the solar disk remained stable to better than ± 3 m s^{-1}. If confirmed, this is an important result since one natural criticism of planet searches from radial velocities of solar–type stars has been a possible sensitivity of photospheric velocities to the phases of star–spot cycles.

4. THE FUTURE

It is fair to say that all of the groups whose work is discussed above have been strongly driven by the search for stellar velocity perturbations by Jupiter–sized planets. These programs are being vigorously pursued and each recognizes that any putative extra-solar planet will only carry conviction if long–term errors can be kept to a few m s^{-1}. To date, no convincing discovery has been announced from PRV.

In the long run, theorists will only be satisfied with planetary systems showing multi-periodicity. For this we must plan measurements with precisions of better than 1 m s^{-1}. In the era of 8- to 10-m telescopes this must be our goal; there will be no excuse, the photons will be available.

5. ACKNOWLEDGMENTS

All of the groups I have cited kindly provided material for this review which greatly simplified my task. This is also an opportunity to thank my colleagues Alan Irwin, Stephenson Yang, and Ana Larson at U. Victoria, David Bohlender and Andrew Walker at UBC, and John Glaspey at CFHT, for their outstanding effort in re-establishing the HF program after Bruce Campbell left in August 1990. My research is supported by grants from the Natural Sciences and Engineering Research Council of Canada.

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7. DISCUSSION

MAZEH: The fact that the giants have variable envelopes does not mean that they do not have low–mass companions. One possible way to distinguish between the few possibilities is to look for very stable periodic variations over a long period of time.

LATHAM: As my collaborator Prof. Mazeh well knows, we have several examples of giant stars with low–amplitude velocity variations which are almost certainly due to orbital motion.

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