Precise Stellar Radial Velocities
ASP Conference Series, Vol. 185, 1999
J. B. Hearnshaw and C. D. Scarfe, eds.

Steps Towards Absolute Accuracy In Radial Velocities[1]

Dag Gullberg

Lund Observatory, Box 43, SE-22100 Lund, Sweden

Abstract. We are developing methods to reach high absolute accuracy in spectroscopic radial velocities for stars of different spectral types. The basic idea is to remove the effects from convection and surface gravity that cause large systematic errors, in order to improve the absolute accuracy of radial velocities by one order of magnitude. This paper briefly describes observations and methodology in computing the radial velocities.

1. Absolute Radial Velocities

Determining absolute radial velocities using the Doppler shifts found in stellar spectra has always been a problem due to miscellaneous effects, both instrumental and stellar intrinsic. While the precision of instruments has improved greatly in the last decade, the absolute accuracy is still problematic since the zero-point is not well defined. The spectroscopic radial velocity, ignoring systematic instrumental errors and apart from the pure line of sight motion of the center of mass, will contain velocity components due to relativistic effects (Lindegren *et al.* 1999), convective blue-shift (Dravins 1999), gravitational red-shift, companions (stellar or planetary), oscillations, activity cycle effects, *etc.* The most important of the these effects, the net effect of convective blue-shift and gravitational red-shift, ranges roughly from -400 ms^{-1} to 400 ms^{-1} going from F0 to K0 main sequence stars.

Using a maximum likelihood estimation method, the radial velocities of individual stars in associations like Hyades and Ursa Major have been determined using astrometric data from Hipparcos (Madsen *et al.* 1999). This, astrometric, radial velocity could be perceived as being the true center of mass motion in the line of sight. The difference between the spectroscopic and the astrometric velocity (see figure 1 left) thus gives a handle on the convective and surface gravity effects (Dravins *et al.* 1999).

But it is not only effects intrinsic to the star, or its neighborhood, that cause problems. What are we really measuring when we cross-correlate a template with an observed spectrum? The choice of template in the cross-correlation is important also, to some level of accuracy. Using the data described in this paper, a difference in computed velocity for two templates (F0 and K0) varies with spectral type as shown in figure 1 (right), resulting in typically 30 ms^{-1} difference in measured value for solar-type stars.

[1]Data were obtained at Observatoire de Haute-Provence, France.

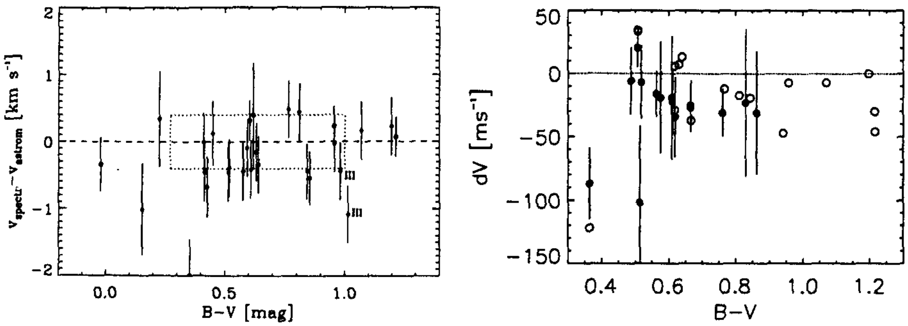

Figure 1. **Left:** When removing the center of mass motion in line of sight from the measured spectroscopic radial velocity, we are left with, mainly, the sum of the convective and surface gravity components. It is estimated to vary between -400 ms^{-1} to 400 ms^{-1} in the spectral type range F0 to K0 for main sequence stars (indicated by the box). Filled circles are Hyades stars, the other are stars in the Ursa Major group. **Right:** The difference of radial velocities for the two Elodie templates, F0 and K0, for some main sequence stars in the program. For noisier spectra (SNR<200), the error-bars have been removed for clarity. The difference for a solar type star between these two templates is typically 30 ms^{-1}.

2. Observations

The échelle spectrograph Elodie at Observatoire de Haute Provence (Baranne *et al.* 1996) has been used to observe, in particular, Hyades stars and stars in the Ursa Major group during two observation runs in 1997, one in February and one in October. Several radial velocity standard stars and other stars were also observed, as was the Moon. The Moon was observed in order to bring the velocities of the two runs to a common frame of reference, linked to the JPL Moon ephemeris.

The resolving power of the instrument is $R \approx 40\,000$ and the wavelength coverage is 389–680 nm spread out over 67 orders. Covering some 300 nm, the spectra obtained are rich in spectral features ($\approx 3\,000$ lines for solar-type stars) allowing us to determine very precise radial velocities.

To obtain low noise spectra without contamination, long integration times with ThAr calibration exposures in between object exposures were used, as opposed to the standard mode of operation which is to do short exposures with the ThAr superimposed in the inter order space, giving simultaneous calibration. We get a precision of about 10 ms^{-1} for our Moon observations.

The reduction software of Elodie, TACOS, computes velocities in pseudo real-time using default templates based on K0 and F0 model atmosphere spectra. In addition, software has been developed at Lund Observatory to compute radial velocities from Elodie data using observed spectra as templates. Specifically the FTS Solar Flux Atlas of Kurucz *et al.* (1984) has been used, giving us radial velocities based on F0, G2, K0 templates in total.

3. The Methodology

To compute the spectroscopic radial velocities for our program stars we use the cross-correlation method. Let S be a dataset containing the observed spectrum, T containing the template. To avoid undesired shift contributions due the parabolic nature of the échelle orders from wide and strong lines residing close to order ends, S is normalized and flipped (i.e. continuum subtracted). The orders are concatenated to cover one continuous range from 389 to 680 nm and subjected to a transient rejection procedure. Furthermore, the two datasets are continuum subtracted and the wavelength scales are made logarithmic.

Edge smoothening is done to remove high frequency components at the edges of both S and T. In order to ensure that the computation is done at the correct point on the abscissa, both datasets are re-sampled (linear interpolation) with equidistant samples using the same sample spacing in both. They are also average-subtracted allowing for the CCF to be computed as $\rho_j = \frac{1}{\sigma_S \sigma_T} \sum_i s_i \cdot t_{i+j}$. The maximum of the emerging CCF is computed by letting the three topmost points define a parabolic function and finding its maximum. Details of the methodology will be discussed elsewhere (Gullberg & Dravins 1999).

During observations, the ThAr calibration will drift. When setting the wavelength scale in the computation of the velocities, the most recent calibration information will be used. But at the mean time of an observation, the wavelength scale will not be the same due to the drift. By interpolating the velocity difference between two consecutive calibrations at the mean time of observation, a correction term is derived. All velocities for the observation program have been corrected in this way. The correction term is also applied to the velocities computed by the Elodie software.

4. The Precision

Estimating the imprecision of the velocities is split up in two parts, one instrumental part (σ_{inst}) and one CCF part (σ_{CCF}). The imprecision of the velocity is $\sigma_V = \sqrt{\sigma_{\text{CCF}}^2 + \sigma_{\text{inst}}^2}$. The drift in velocity of the ThAr calibration exposures tends to behave like a random walk, a Wiener process. One important characteristic of such a process is that $E[\Delta V^2] \propto \Delta t$. That is, the expectation of the velocity difference squared between two points in time is proportional to the difference in time. By using the time difference between the mean time of observation and the most recent calibration, σ_{inst} can be estimated. Estimated errors are shown in figure 2 (left). The stability of the instrument was improved in the period between the two runs, resulting in a very stable instrument during the October run.

σ_{CCF} is the uncertainty in determining the maximum of the CCF. It is based on the curvature of the CCF, the local noise in observed flux and the local slope of the template (adjusted for the shift due to the velocity). Generally, $\sigma_{\text{CCF}} = \sum_i [t_{i-1} - t_{i+1}]^2 s_i / (2c_0 - c_1 - c_{-1})$. The c_i are the three top most points of the CCF. σ_{CCF} as a function of $(B - V)$ is shown in figure 2 (middle and right).

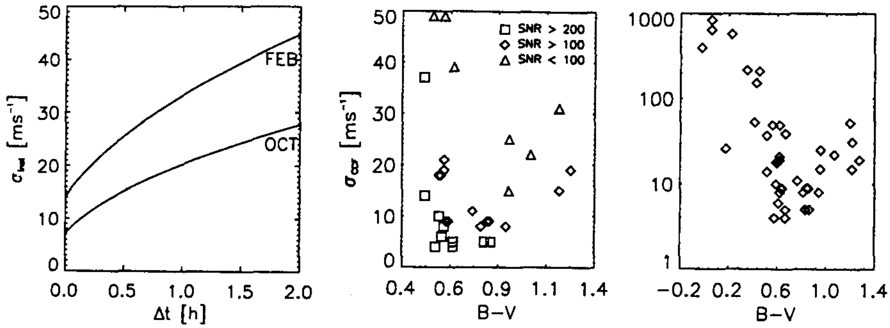

Figure 2. **Left:** The drift in calibration with time causes an increased uncertainty of the determined velocity with increased exposure time (using our mode of operation). In this diagram are shown the estimated errors from this calibration drift as a function of the time between most recent ThAr exposure and the mean time of the observation. The refurbishment of Elodie in mid 1997 gave a very good instrumental stability during the October run. **Middle and Right:** The estimated errors in the determination of the maximum in the CCF as a function of color (based on main sequence stars only). The error grows exponentially towards earlier-type stars.

5. Discussion

The aim of the project is to find some way to correct for the convection and surface gravity effects in spectroscopic radial velocities. Although most points in figure 1 (left) in the range F0 – K0 appear to be where expected, determining a correction function at this point seems difficult. The large error-bars are mainly due to the inaccuracy of the astrometric radial velocities; however, other systematic effects from stellar or planetary companions, activity cycle, *etc.*, are also embedded in the values. An effort to disentangle the convective component is described by Gullberg (1999) where differential shifts between groups of lines are investigated. More observations will of course improve the quality of any correction function computed.

Discussion

Mayor: I would comment that changing the template for the cross-correlation would evidently induce a small change in the velocity. The templates F0 and K0 do not have the same spectral lines in common. As a consequence of convective motions, the selection of spectral lines certainly affects the apparent velocity by a few 10 m/s.

References

Baranne, A., *et al.*, 1994, A&ASuppl., 119, 373
Dravins, D., 1999, this colloquium
Dravins, D., Gullberg, D., Lindegren, L. & Madsen, S., 1999, this colloquium
Gullberg, D., 1999, this colloquium
Gullberg, D. & Dravins, D., 1999, A&A, in preparation
Kurucz, R. L., Furenlind, I., Brault, J., 1984, National Solar Observatory Atlas
Lindegren L., Dravins, D. & Madsen, S., 1999, this colloquium
Madsen, S., Lindegren, L. & Dravins, D., 1999, this colloquium