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Radial Velocity Techniques

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Abstract. We review the performance of the CfA Digital Speedometers for measuring stellar radial velocities and outline the remarkable improvement that is becoming available with a new generation of instruments. Large gains can be expected for the velocity precision, limiting magnitude, and number of objects observed.

1. Introduction

The pioneering effort by Gunn & Griffin (1979) to survey the radial velocities of a large number of faint stars in the globular cluster M3 demonstrated the feasibility of this type of research and signaled a rebirth of interest in stellar radial velocity research. Instruments capable of mass-producing observations for large numbers of faint late-type stars with precisions better than 1 km s^{-1} have been developed at several observatories. These instruments have been applied to a wide variety of studies, such as cluster membership and dynamics, Galactic structure and evolution, and distances to pulsating stars. A major area of research has been surveys of spectroscopic binaries, where there are important new results on the characteristics of binaries in a wide variety of stellar populations: pre-main-sequence stars, solar-type dwarfs, cool dwarfs, halo and thick-disk dwarfs, open cluster dwarfs and giants, globular cluster giants, supergiants, and eclipsing binaries. These observations are bringing into focus some tough challenges to the theoreticians. Can a general theory of star formation be developed that predicts the binary characteristics that we actually observe? What sets the initial distribution of secondary masses, orbital eccentricities, and periods? How do orbits evolve with time, both with and without mass transfer and mass loss? Can we understand orbital circularization well enough to use it as a clock for dating the age of coeval populations of binaries? Can we understand in detail the chemical abundances in systems where one or more of the stars has evolved and transferred mass? Can we model the dynamical evolution of clusters, and the role that binaries play in this evolution?

As an example of the current generation of instruments that have been in use for more than a decade, in Section 2 we summarize the performance of the CfA Digital Speedometers. Then, in Section 3 we estimate the improvements in velocity precision, limiting magnitude, and number of objects which should be achievable with a new generation of instruments.

2. CFA Digital Speedometers

At the CfA we have been mass-producing stellar radial velocities for more than 15 years, using nearly identical Digital Speedometers (Latham 1985, 1992) on three different telescopes: the 1.5-m Wyeth Reflector in Harvard, Massachusetts, and the 1.5-m Tillinghast Reflector and Multiple Mirror Telescope atop Mt. Hopkins, Arizona. Our instruments are echelle spectrographs coupled with intensified photon-counting Reticon detectors, recording digital spectra for a single echelle order centered near 5187 Å and covering a wavelength range of 45 Å. For the determination of radial velocities we use the correlation software developed by Tonry and Davis (1979) as modified by Wyatt (1985) and implemented in the task XCSAO (Kurtz et al. 1992) under the IRAF[1] environment. One of the advantages of the digital approach is the flexibility it allows in the choice of the template spectra to be used for the correlations. We have found that the spectrum of the sun gives good correlations for a remarkably large range of spectral types, and most of our velocities have been derived using a high-count exposure of the dusk sky as the template. Over the past few years we have often used calculated spectra as templates, especially for correlations of rotating stars (Nordström et al. 1994), of metal-poor stars (Carney et al. 1994), and of stars with composite spectra (Torres et al. 1995). Our library of synthetic spectra was calculated by Jon Morse for a grid of Kurucz (1992a, b) model atmospheres.

A typical spectrum observed with the CfA Digital Speedometers has less than 100 detected photons per 8.3 km s^{-1} resolution element, corresponding to a total of about 30,000 detected photons. For example, Figure 1 shows the spectrum (upper panel) from a 4-min exposure with the 1.5-m Tillinghast Reflector of the $V = 12.9$ star Sanders 1147 in the old open cluster M67 and the corresponding correlation function (lower panel) using a synthetic spectrum with $T_{eff} = 6500$ K, [m/H] = 0.0, $\log g = 4.5$, and $v \sin i = 0$ km s^{-1}. The R value for this correlation is 8.7 and the estimated velocity error is 0.83 km s^{-1}. With a total of only about 8000 detected photons, this observation is in the regime where photon noise dominates the velocity error. This is demonstrated by Figure 2,

where we plot the r.m.s. velocity error versus the total detected photons. The filled circles were derived from multiple short exposures of the zenith sky taken with the CfA Digital Speedometer on the 1.5-m Wyeth reflector on a clear day without moving the telescope. The sky spectra were bracketed by thorium-argon exposures and reduced in exactly the same way as normal stellar spectra. Neutral density filters were used together with a variety of exposure times to cover a range of more than 1000 in the total detected photons.

For exposure levels below about 100,000 photons the velocity errors follow the expected square-root dependence on the total detected photons. At higher exposure levels the error curve flattens out, as other sources of error become important. For the sky exposures we needed rather long exposure times to achieve the highest exposure levels, due to count-rate limits in the photon-counting de-

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[1] IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

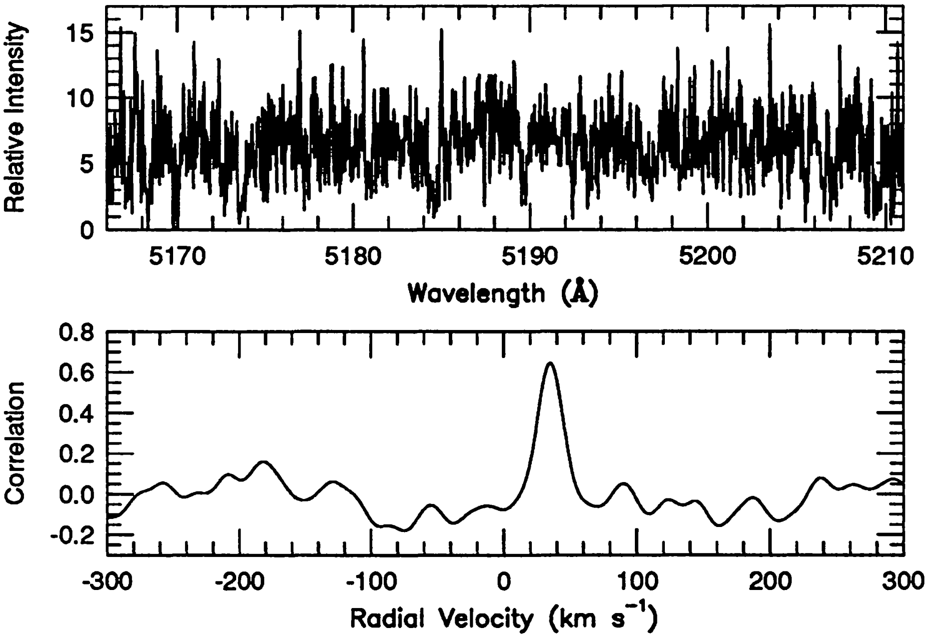

Figure 1. The spectrum (upper panel) from a 4-min exposure with the 1.5-m Tillinghast Reflector of the $V = 12.9$ mag star S1147 in the old open cluster M67 and the corresponding correlation function (lower panel) using a synthetic spectrum as the template. The R value for this correlation is 8.7 and the estimated velocity error is 0.83 km s^{-1}.

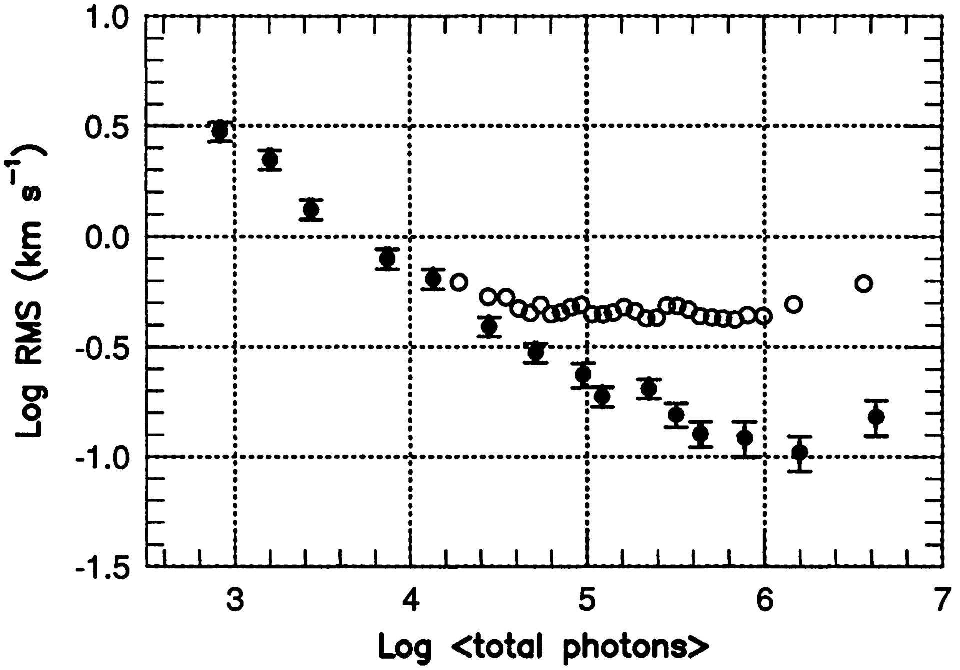

Figure 2. The r.m.s. velocity errors observed for sequences of sky exposures (solid circles) and for some well-observed IAU standard stars (open circles). The stellar velocities span more than 10 years, and demonstrate the limits set by long-term systematic errors.

tector. Temperature drifts in the spectrograph became a significant source of velocity error for the longest sky exposures, causing the error curve to flatten out. The open circles in Figure 2 show the r.m.s velocity errors observed for a couple dozen IAU standard stars which have been well observed with the CfA instruments for more than 10 years. The error curve for these stars levels off a little below 0.5 km s^{-1}, indicating that at high exposure levels the errors for stars are not dominated by photon statistics, but rather by various systematic errors such as nightly drifts in the zero point of the CfA velocity system.

3. Potential Performance Gains

By almost any measure the CfA Digital Speedometers have been successful. Over a period of more than 15 years they have been used to measure a total of approximately 125,000 radial velocities for nearly 100 different research projects involving a total of several thousand stars. These data have been used in dozens of research papers. Nevertheless, the CfA instruments operate at a tiny fraction of their potential efficiency, because the spectral coverage is limited to a single echelle order and the detective quantum efficiency of the intensified Reticon detectors is limited to about 10%. In this section we consider the gains in performance which should be available with echelle spectrographs using modern CCD detectors on giant telescopes.

3.1. Single-Object Multi-Order Magnitude Limits

We first consider the case of a single-object multi-order echelle spectrograph mounted directly on the telescope. Even with the largest telescopes it is possible to build a spectrograph with a large enough beam so that essentially all the light in a 1-arcsecond image passes through the slit, so we neglect slit losses. For very high resolution, e.g. better than a few km s^{-1}, it may be necessary to use slits narrower than 1 arcsecond, in which case slit losses need to be taken into account.

To estimate the benefit of increasing the spectral coverage, we use for guidance the argument that in the photon-limited case the velocity precision depends only on the total number of photons detected, and not on the wavelengths covered. This is true only if all wavelengths have the same population of spectral lines. In practice, some wavelength regions contain better lines than others, and thus provide more velocity information. Even though it is possible to build an echelle spectrograph and CCD detector that covers as much as 100 times more spectrum than the CfA Digital Speedometers, 4500 Å instead of 45 Å, we estimate that the net improvement in performance would be degraded by about a factor of four, to a factor of only 25.

The photon-counting intensified Reticon detectors used in the CfA Digital Speedometers have peak detective quantum efficiencies of about 10%, while modern CCD detectors can deliver an average efficiency of something like 80% over quite a wide spectral range. Therefore, we adopt a factor of 8 for the improvement that the best CCDs would provide.

Taken together, the improved spectral coverage and detective quantum efficiency of a modern single-object multi-order instrument would provide a factor of about 200 in performance compared to the CfA Digital Speedometers. This corresponds to reaching stars which are nearly 6 mag fainter for a given telescope and exposure time. For example, on the 1.5-m Tillinghast reflector, an exposure of about 1 minute should deliver a precision of 1 km s^{-1} for a $V = 18$ mag late-type star, compared to $V = 12$ for the present instrument. Indeed, there are already reports (Mayor 1995) that the ELODIE instrument on the OHP 1.8-m telescope has been able to reach fainter than magnitude $V = 17.5$ with a precision of 1 km s^{-1}.

Moving to a larger telescope should gain as the area of the primary. For example, moving to the MMT after it is converted to a single 6.5-m primary should provide an additional gain of 3 magnitudes, and thus should reach $V = 21$ with a 1-minute exposure. These comparisons assume that other noise sources, such as the noise associated with CCD readout or with the subtraction of dark frames or sky frames, are negligible and that photon noise dominates. It should be possible to achieve even fainter limits with longer exposure times, but only if these other sources of noise can be controlled.

3.2. Single-Object Multi-Order Precision Limits

If the effects of all systematic errors can be reduced so that the precision of a velocity is limited only by the photon statistics, then the velocity precision should improve as the square root of the total number of detected photons. In this case the factor of 200 gained by going to a modern instrument should allow an improvement in the precision by a factor 14, from 1 km s^{-1} to 70 m s^{-1} for a 1 minute exposure on a $V = 12$ mag star with a 1.5-m telescope. Extrapolating to a 10-m telescope, it should be possible to achieve a precision of 2 m s^{-1} on a $V = 12$ mag star with an exposure of 30 minutes!

Of course, it is not a trivial challenge to reduce all the systematic errors to below the level of 1 m s^{-1}, especially the errors due to long-term (i.e. monthly and yearly) drifts in the zero point of the velocity system. Strategies such as the use of a fiber feed and/or an iodine absorption cell may be needed to achieve this level of precision. Fortunately, these strategies imply only a modest penalty to the efficiency of the instrument, on the order of a factor of 0.5. Indeed, there are already reports (Vogt 1995) that the HIRES instrument on the Keck telescope has been able to achieve a precision better than 2 m s^{-1}.

3.3. Mult-Object Single-Order

Now we consider the case of a single-order echelle instrument fed by a multi-object fiber positioner, such as the HYDRA instrument on the WYIN telescope (Barden 1995). We take the wavelength coverage to be the same as the CfA Digital Speedometers, but still invoke the factor of 8 improvement provided by a modern CCD detector. The transmission penalty for using fiber feeds is about a factor of 0.5, but the gain in the number of objects is about a factor of 100. In survey mode where large numbers of objects are available at one time in the field of the telescope, the multi-object instrument on a 6.5-m telescope should be more efficient than the 1.5-m Tillinghast reflector by a factor of 7,500! This improved efficiency could equally well be translated into measuring more objects or into reaching fainter limits. For example, with a 15 minute exposure a 6.5-m telescope should be able to measure velocities with a precision of 1 km s^{-1} for 100 late-type stars with magnitude $V = 19.5$.

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Discussion

Clarke: Is the eccentricity-period diagram for M67 indistinguishable from that for the local G dwarfs?

Latham: The two diagrams have a similar appearance. A detailed comparison is complicated by the fact that the field population is composed of stars with a spread of ages peaking near 3 Gyr, while M67 has an age of about 5 Gyr. In particular, some of the nearby field binaries may be a lot younger than M67, with much less time for their orbits to circularize. The longest circular orbit among the field binaries might prove to be a much younger system, and thus would not be a reliable marker of the transition from circular to eccentric orbits.

Verbunt: The circularization depends on $(R/a)^8$, where R is the stellar radius and a is the separation of the stars. This means effectively that a binary either circularizes completely or not at all. The age only enters via the size R of the star. So, the distribution of eccentricity vs. period should be the same for the field and for M67.

Leonard: Have you found any triple systems in your survey of M67?

Latham: So far only S1234 has been definitely identified as a triple. We expect more triples to show up with additional observations.

Livio: Is there a possibility to use ELODIE to obtain data on masses smaller than 2 Jupiter masses? Marcy has already placed limits on the existence of 2 Jupiter mass companions for 30 stars.

Mayor: The emphasis here is to do many stars, about 400, in the range 3 to 100 Jupiter masses. This range has not been fully explored. Hence this effort complements Marcy's.