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Surveys of Spectroscopic Binaries at the Center for Astrophysics

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ABSTRACT: For more than a decade we have been measuring stellar radial velocities with three almost identical digital speedometers on telescopes in Arizona and Massachusetts. By now we have accumulated nearly 100,000 measurements with a typical precision of better than 1 km s^{-1}. One of the main scientific applications has been surveys of binaries in several different stellar environments, to study the frequency and orbital characteristics of binaries in a variety of stellar populations. A main goal is to confront theories of binary formation and evolution with observational results. With various collaborators we have investigated the binary populations among pre-main–sequence stars, in the Hyades and M67 open clusters, and in the Carney–Latham proper–motion sample. Thus, we have data for coeval samples of binaries covering a wide range of ages. One result is clear evidence for evolution of binary orbits. The orbital period at which there is a transition from circular to eccentric orbits gets longer for older samples of binaries, presumably due to tidal circularization. Another result is that the frequency of binaries does not seem to depend on the stellar population. Binaries are just as common among the oldest stars in the halo of our Galaxy as among the younger stars in the disk.

1. INTRODUCTION

Research using stellar radial velocities has experienced a rebirth of interest over the past decade, as a result of the development of instruments at several observatories capable of mass–producing observations for large numbers of faint late–type stars with precisions better than 1 km s^{-1}. 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. One of the major areas of effort has been surveys of spectroscopic binaries, where there are exciting new observational results on the characteristics of binaries in a wide variety of stellar populations: pre-main–sequence stars, main–sequence solar–type dwarfs, cool dwarfs, halo and thick–disk dwarfs, open cluster dwarfs, open cluster giants, globular cluster giants, field late–type 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?

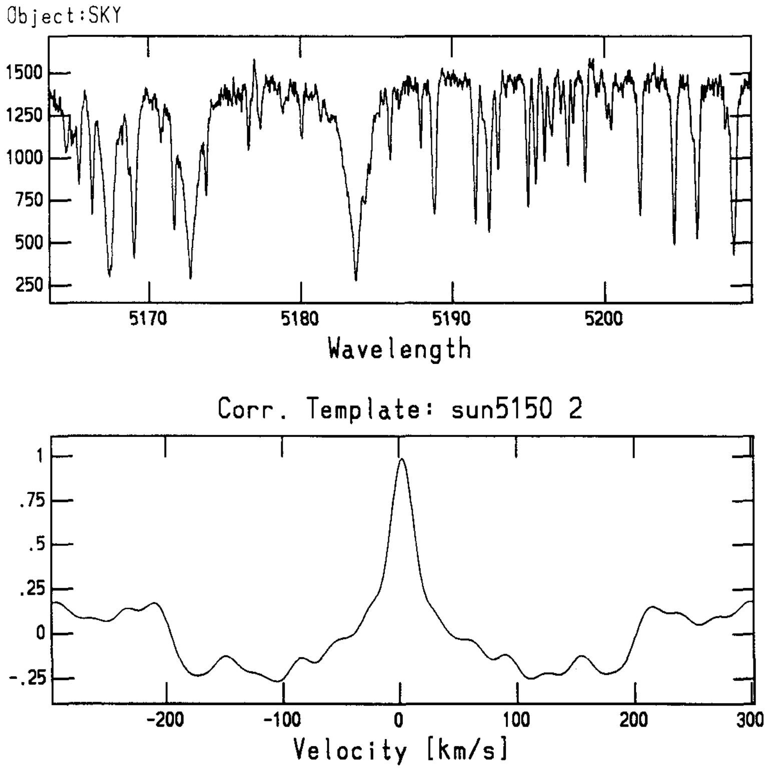

FIGURE 1. The echelle spectrum of the dusk sky used as the template for our standard velocity correlations. The original exposure is reduced file number 7195, obtained with the digital speedometer on the 1.5-m Tillinghast Reflector at Mt. Hopkins. The prominent features in the left half of the spectrum are the magnesium b lines. The lower panel shows the plot of the correlation against a calculated solar spectrum.

2. CFA DIGITAL SPEEDOMETERS & VELOCITY SYSTEM

At the Harvard–Smithsonian Center for Astrophysics (CfA) we have been mass–producing stellar radial velocities for more than a decade, using nearly identical digital speedometers (Latham 1985) 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 & Davis (1979) as modified and implemented by Wyatt (1985). 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

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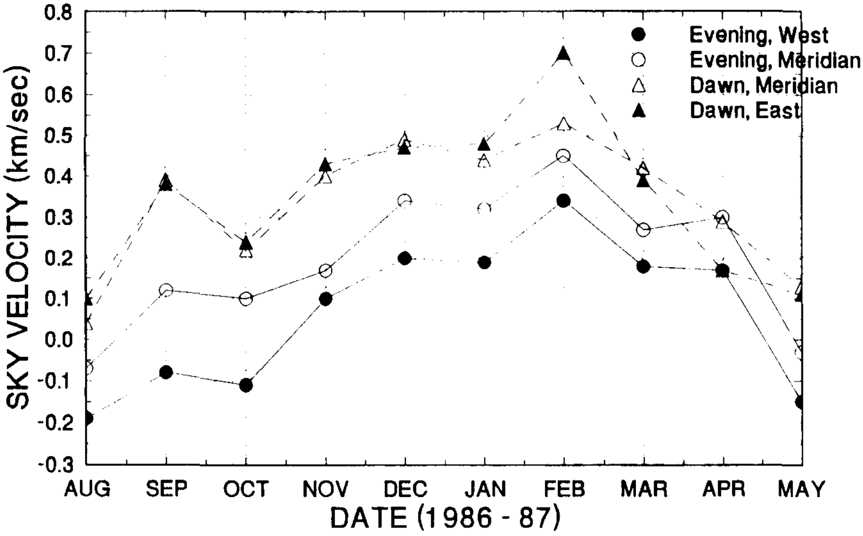

FIGURE 2. History of the sky velocities derived from dusk (circles) and dawn (triangles) exposures over a 10-month period with the 1.5-m Wyeth Reflector at the Oak Ridge Observatory.

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.

The actual exposure which we have been using in our standard reductions is shown in Figure 1, together with a plot of its correlation against a solar spectrum calculated by Jon Morse using one of the new Kurucz (1992) model stellar atmospheres. The R value (Tonry & Davis 1979) for this correlation is 73 and the estimated velocity error is 125 m s^{-1}. This must be close to the limiting precision that can be achieved for a single exposure with the standard configuration of our digital speedometers, because the signal-to-noise performance of the detector can not be much improved in routine operation without expending substantial additional effort.

Our echelle spectrographs were not designed specifically for radial-velocity work, and they suffer from large temperature effects and mechanical flexure as a result of being mounted on our telescopes at the Cassegrain focus. To monitor the zero point of the velocity system for each instrument, on each night of an observing run we take multiple exposures of the dusk and dawn sky and usually observe two or more radial-velocity standard stars during the night. In a typical run we often have more than 50 sky exposures, and the rms deviation of a single sky velocity from the mean for the run is usually in the range 150 to 250 m s^{-1}. From run to run the mean sky velocity rarely shifts by more than a few hundred m s^{-1}, unless there has been some major change or adjustment to the instrument. From time to time we see problems in our velocity zero point at the level of a few hundred m s^{-1}. For example, in Figure 2 we show the history

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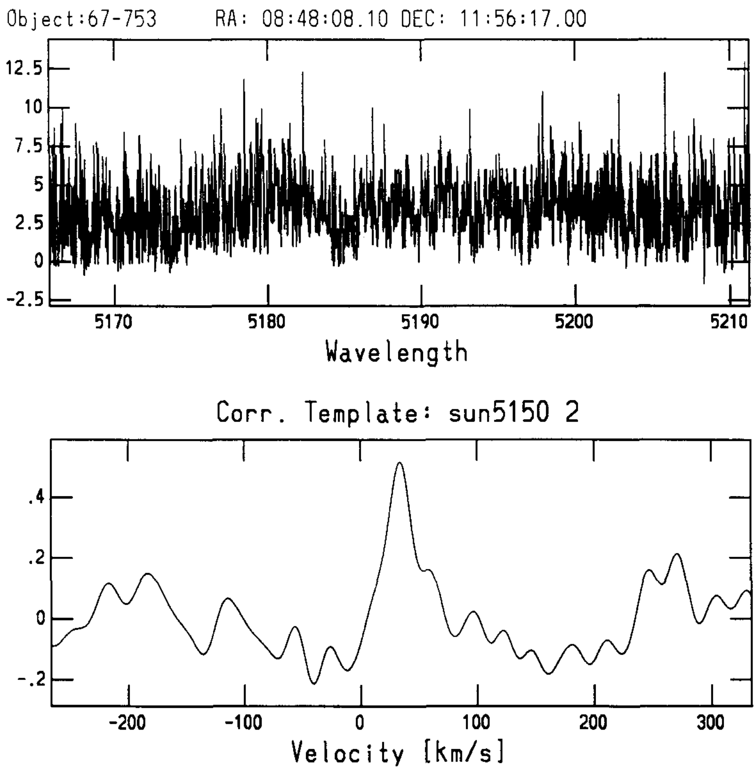

FIGURE 3. Spectrum of S753, a V = 15.0 main–sequence star in the old open cluster M67. The exposure time was 20 minutes with the 1.5-m Tillinghast Reflector at the F. L. Whipple Observatory. Despite the weak exposure of only 3 counts per 1.8 km s^{-1} pixel, the correlation peak is unambiguous and gives an estimated velocity error of 1.2 km s^{-1}.

of the average sky velocities from the Wyeth Reflector for a period of almost a year. On top of a clear seasonal variation in the velocity zero point there is also a systematic shift between dusk and dawn. Presumably, both trends have resulted from temperature effects. The dawn–dusk trend must be coupled with some instrumental misalignment, because it is usually much smaller than shown in Figure 2.

The performance of the sky exposures suggests that we are able to set the velocity zero point for each run on each telescope to an accuracy of perhaps 100 or 200 m s^{-1}. This is considerably better than the precision of our individual measurements of stellar velocities, where the exposure levels are usually much weaker. Judging from cases where we have dozens of observations spanning many years, we routinely achieve an rms precision of better than 0.5 km s^{-1} for late–type stars. This performance can easily be degraded by a factor of 2 for extremely metal–poor stars, where the lines are very weak. For stars which

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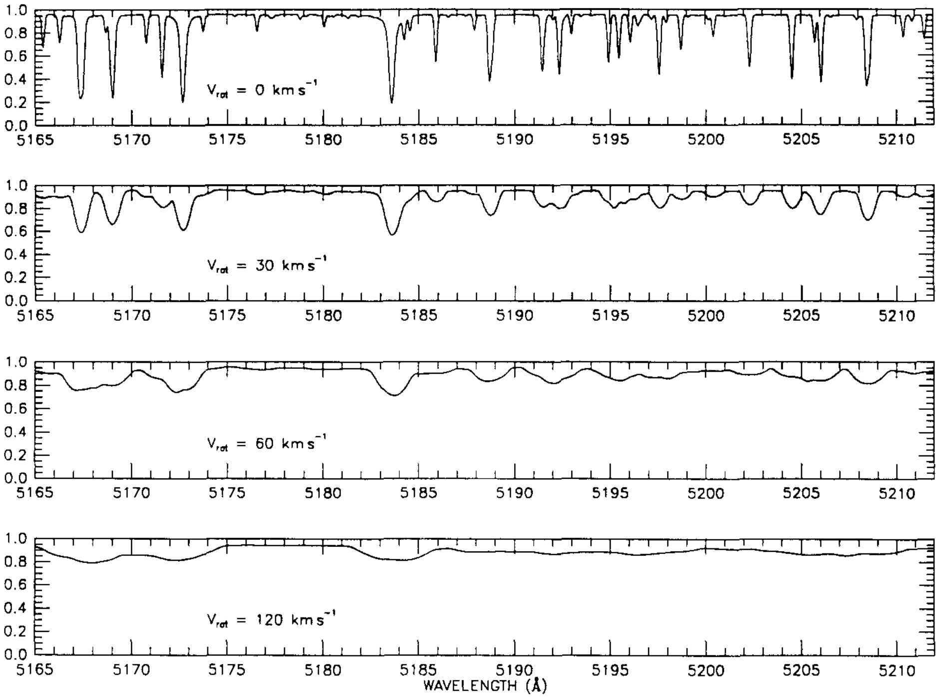

FIGURE 4. Calculated spectra with rotational velocities of 0, 30, 60, and 120 km s^{-1} for a Kurucz model stellar atmosphere with effective temperature 7000 K, log surface gravity 4.0, and solar metallicity. To derive reliable velocities for rapidly rotating stars requires exposures with much better signal–to–noise, and stars which rotate more rapidly than 120 km s^{-1} do not in general give reliable velocities with our system.

are much hotter than the sun, especially those which are rapidly rotating, the precision can be considerably worse than 1 km s^{-1}.

As an independent check of the velocity zero point set by the sky exposures, we have made hundreds of observations of minor planets, whose velocities can be predicted with exquisite accuracy from their well–established orbits based on astrometry. These two different schemes for establishing the zero–point of the CfA velocity system agree to better than 100 m s^{-1} (Latham & Stefanik 1992).

At CfA we have emphasized large surveys of faint stars. Most of our echelle spectra have fewer than 20 counted photons per 1.8 km s^{-1} pixel, and the photon noise is usually the main contributor to the uncertainty in a single measurement. For example, in Figure 3 we show a 20-min exposure, taken with the 1.5-m Tillinghast Reflector, of S753, a V = 15.0 main–sequence star in the old open cluster M67. Despite the low average count level of 3 photons per pixel in the continuum, the correlation peak is unambiguous and the estimated uncertainty in the velocity is a respectable 1.2 km s^{-1}.

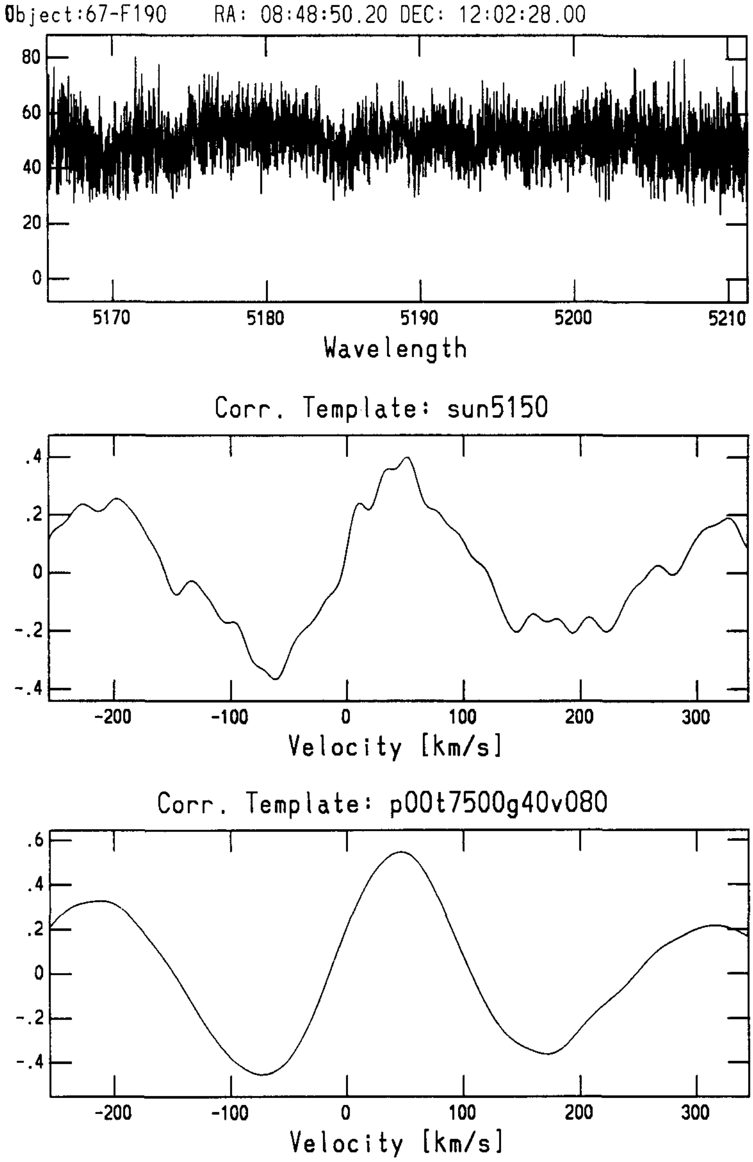

FIGURE 5. A spectrum of Fagerholm 190, a classical blue straggler in M67. The correlation against a calculated template rotating at 80 $km\,s^{-1}$ gives a much better velocity than the calculated sky template.

3. CALCULATED TEMPLATES & XCSAO

Over the past two years there have been two major developments in our data reductions. The velocity correlations are now carried out using XCSAO (Kurtz *et al.* 1992), a special task operating inside the Image Reduction and Analysis Facility (IRAF) environment. In addition, a large grid of synthetic spectra suitable for use as correlation templates has been calculated by Jon Morse using the new grid of Kurucz (1992) model atmospheres.

The new calculated templates have been used to derive improved velocities for extremely metal–poor stars, and have proven to be especially effective for rapidly–rotating stars. For example, the effects of rotation are shown in Figure 4, where we plot calculated spectra with rotational velocities of 0, 30, 60, and 120 $\mathrm{km\,s^{-1}}$ at effective temperature 7000 K, log surface gravity 4.0, and solar metallicity.

Choosing an optimum calculated template can easily improve the velocity precision by more than a factor of 2 for a rapidly–rotating star. In Figure 5 we show the example of Fagerholm 190, a classical blue straggler in M67. The correlation against a template rotating at 80 $\mathrm{km\,s^{-1}}$ gives a much better velocity than the standard sky template.

4. CFA BINARY SURVEYS

With various collaborators we have undertaken long–term surveys of the binary populations in several different stellar environments, including pre-main–sequence stars (Mathieu 1992), the Hyades (Stefanik & Latham 1992), the old open cluster M67 (Latham *et al.* 1992a), and the Carney–Latham survey of proper–motion stars (Latham *et al.* 1992b), as reported elsewhere in this volume. These surveys provide coeval samples of binaries that cover a wide range of ages.

One result is clear evidence for evolution of binary orbits (Mathieu *et al.* 1992). The orbital period at which there is a transition from circular to eccentric orbits gets longer for older samples, presumably as a result of tidal circularization during the main–sequence phase. For orbits with periods longer than the transition, the eccentricity distributions are indistinguishable among the various populations of binaries. Also, the frequency of spectroscopic binaries does not seem to depend on the stellar population; for periods less than 2000 days the frequency appears to be close to 20% in almost every sample of main–sequence binaries that has been studied carefully. Binaries are just as common among the oldest stars in the halo of our Galaxy as among the members of the disk and open clusters, which are far younger.

5. ACKNOWLEDGMENTS

Many people have contributed to the success of the CfA stellar radial velocity programs. The main scientific collaborators have been: Bruce Carney, University of North Carolina (surveys of proper–motion stars, distances to pulsating stars); Tsevi Mazeh, Tel Aviv University (searches for low–mass companions of stars, orbital solutions and analysis); Robert Stefanik, CfA (observing, binary surveys); Bob Davis, CfA (observing, data management); Bob Mathieu, University of Wisconsin (pre-main–sequence binaries, open clusters); Guillermo Torres, CfA (surveys of binaries, analysis); Alejandra Milone, CfA (blue stragglers, open clusters); John Laird, Bowling Green State University (metallicities); Larry Marschall, Gettysburg College (pre-main–sequence stars, X-ray binaries); Jon Morse, University of North Carolina (calculated spectra, blue stragglers); Jesper Storm, European Southern Observatory (distances to pulsating stars); Roger Griffin, Cambridge University (open clusters); Johannes Andersen and Birgitta Nordström, Copenhagen University Observatory (F stars, eclipsing binaries); Michel Mayor and Gilbert Burki, Geneva Observatory (standard stars). John Geary and Bill Wyatt deserve special thanks for their vital contributions to the hardware and software, respectively. Many of the observations have been made by Ed Horine, Jim Peters, Skip Schwartz, Joe Caruso, Joe Zajac, and Dick McCrosky.

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7. DISCUSSION

MATHIEU: This morning, Helmut Abt asked me about the long–period circular orbits in our M67 eccentricity distribution, since yesterday I had noted that such orbits were absent among pre-main sequence and main sequence binaries. In M67, the long-period circular orbits have giant primaries, so their circularity is not a surprise. But in this line, I have a question for the audience. Does anyone know of a long–period circular binary where both components are definitively main sequence stars?

TOKOVININ: How could you reconcile the fact of non-zero eccentricity of the HD 114762 companion and its short period with characteristics of Jupiter-like planets?

LATHAM: I do not know of any theory that successfully describes the formation of a giant planet in an orbit as close as Mercury's to a solar-type star. But, neither do I know of a theory that successfully describes the formation of close stellar companions with the characteristics we observe for short-period binary stars. This remains a puzzle and a challenge that demands a satisfactory explanation.

ABT: What is your bright limit in the Hyades?

LATHAM: We can now work into the A stars up to a temperature of about 10,000 K and up to a rotational velocity of about 100 km s^{-1}. This is a new development of our technique, where we use calculated spectra for the templates, carefully chosen to match the temperature, gravity, metallicity, and rotation of the observed star.

ZINNECKER: Can you remind us of the result for the frequency of spectroscopic binaries among the halo stars?

LATHAM: The frequency of spectroscopic binaries in our halo sample is indistinguishable from the frequency in the Abt & Levy and the Duquennoy & Mayor samples of nearby solar dwarfs, as shown by Guillermo Torres in his thesis.

BOSS: Could you comment on Cochran and Hatzes recent argument that the HD 114762 system is viewed nearly face-on because of the low stellar rotational velocity of the primary?

LATHAM: Cochran and Hatzes derived a very low value for the projected equatorial velocity of rotation for HD 114762 using high quality coudé spectra. This result may suggest that the orbit is viewed nearly pole on, but it certainly does not prove the point. We do not know *a priori* what the angle is between the axial rotation of the primary and the orbit of the companion, and we do not know *a priori* what the value is for the intrinsic equatorial velocity of rotation. Indeed, HD 114762 may have a very slow intrinsic rotation, because it is considerably older than the sun and yet has the same temperature.