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Novel Interferometer Spectrometer for Sensitive Stellar Radial Velocimetry

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Abstract. We describe a new kind of stellar radial velocimeter based on the series combination of a wide angle Michelson interferometer and a disperser, and which we call a fringing spectrometer. The simplest instrument response of the interferometer produces smaller instrumental noise, and the low resolution requirements of the disperser allows high efficiency and creates an etendue capability which is two orders of magnitude larger than current radial velocimeters. The instrument is compact, inexpensive and portable. Benchtop tests of an open-air prototype shows the short term instrumental noise to be less than 0.76 m/s. A preliminary zero point drift of 4 m/s is already competitive with traditional instruments, in spite of the lack of obvious environmental controls and a known interferometer cavity length drift. We are currently installing cavity stabilization and other improvements that will lead to testing on starlight.

1. Introduction

Velocity noise in current stellar Doppler velocimeters used to detect extrasolar planets typically ranges 3 to 13 m/s, with the best noise from the Lick Observatory and Keck HIRES grating spectrometers (Butler 1996). This noise level is insufficient to reliably detect a saturn-like planet, which would have a 3 m/s amplitude velocity signature, and insufficient to resolve stellar photosphere dynamics having 1–2 m/s amplitude analogous to solar 5-minute ringing. A component of this observed noise is due to photon statistics, another due to the source such as unresolved motion of photosphere, and the remainder due to instrumental noise.

Our goal is to develop a new kind of stellar radial velocimeter which has lower instrumental noise and which could be made very light efficient. Both goals can be achieved by combining a wide angle Michelson interferometer in series with a disperser. The simple and sinusoidal instrument response of the interferometer produces smaller instrumental noise, and the low resolution requirements of the disperser allows it to be optimized for high efficiency instead of narrow point spread function (PSF). Ancillary benefits include low cost, com-

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pactness and portability. These alone make the device attractive, as it allows smaller institutions to join in the search for extrasolar planets with lower capital investment.

A further advantage is that the instrument etendue capability is two orders of magnitude larger than for current radial velocimeters ($9\text{x}10^{-4}$ sr cm^2 vs. $5\text{x}10^{-6}$ sr cm^2). In addition to allowing multiple targets, this indirectly improves efficiency by allowing the use of tolerant wide diameter optical fibers, so to reduce clipping the wings of a blurry star image. This makes it more feasible to use poorer optical quality but inexpensive large collecting area "light buckets" for Doppler spectroscopy. The surplus etendue can also be used to illuminate several interferometers in parallel. When these have different path length differences, the additional fringe shift information can determine the spectral lineshape asymmetry shift simultaneous to the Doppler shift. This provides additional information about the photosphere dynamics, which is increasingly relevant when seeking velocity signatures in the $\sim$3 m/s range.

Current stellar radial velocimeters are based on the diffraction grating. Their instrumental noise is due to difficulty in accurately characterizing the PSF, so that its convolving effects can be removed from the spectral data. Since a grating is a N-beam interference device, where N is in the hundreds or thousands, its PSF has at least N degrees of freedom. That is, the PSF is not a simple mathematical function. Furthermore, the PSF varies with average wavelength across the spectrum so that a family of PSF model functions are needed, and the PSF varies in complicated ways under the insults of air convection, thermal gradients and coating degradation.

2. Fringing spectrometer instrument

Our approach is to use a 2-beam interference device (an interferometer) to resolve the Doppler shifts, so that the relevant instrument response has only 3 degrees of freedom: fringe phase, amplitude and offset. Since the interferometer instrument response is sinusoidal, it is a standard mathematical function. The vastly simpler instrument response allows smaller velocity noise. Under the same insults of air convection, thermal drifts, coating degradation etc., the instrument response remains the same mathematical form. This constancy gives the data analysis algorithm robustness, as well as processing speed. Our preliminary codes (written in high level macro language, not yet optimized for speed) process at about 1 **minute** CPU time per velocity datum on a Macintosh. In comparison, Butler and Marcy et al. report data processing speed of 2 **hours** per datum on a Sparc10 workstation (Butler 1996).

However, an interferometer used alone on broadband absorption spectra such as starlight will produce poor signal to noise, because fringes from neighboring spectral lines overlap and confuse their phases. This has discouraged previous use of broadband interferometry for this application. Our solution is to separate the major spectral lines by combining the interferometer in series with a low resolution disperser, to produce fringing spectra. We call our device a fringing spectrometer or spectrally dispersed interferometer.

Figure 1 shows a photograph of our first prototype fringing spectrometer whose purpose is to test the ability to measure broadband fringe shifts with

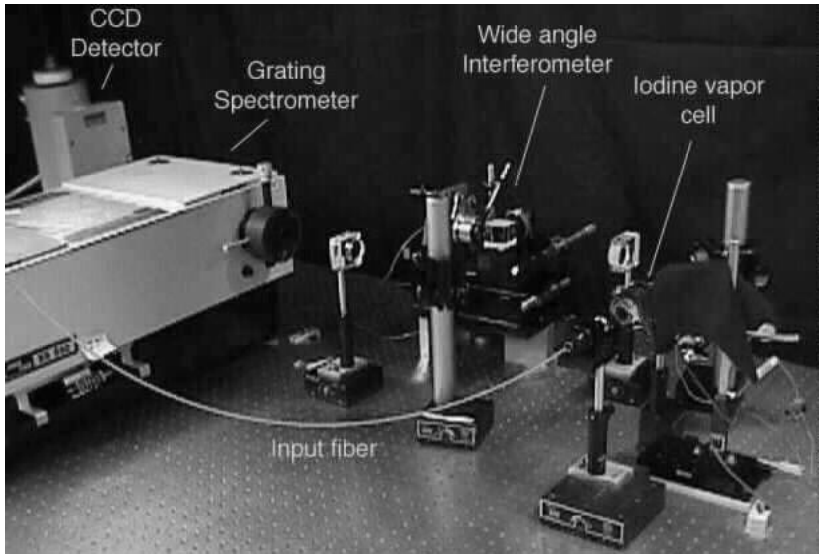

Figure 1. Our first prototype fringing spectrometer is the series combination of an iodine vapor cell, interferometer, and conventional 0.6 meter grating spectrometer.

sunlight or convenient laboratory sources. The source light conducted through an optical fiber can pass through an iodine vapor cell inserted into the path. This provides an absolute reference absorption spectrum. The light passes through a wide-angle Michelson interferometer (Hilliard 1966) having approximately 11.5 mm path length difference. The interferometer imprints fringes to the beam which are imaged to the slit of the disperser, the fringes being perpendicular to the dispersion direction.

In contrast with Fourier transform spectrometers, our instrument has a nominally fixed path length difference and detects the Doppler shift through the change in fringe phase, averaged over all spectral channels. (For an 11.5 mm delay and 540 nm average wavelength, a 1 m/s Doppler shift corresponds to 1/14000th of a fringe.) However, one of the interferometer mirrors is attached to a PZT actuator so that the path length can be dithered in small ($\simeq 90^\circ$) phase steps. Making repeated measurements while stepping the overall phase helps distinguish true fringes from similar appearing intensity variations due to other causes. However, it is possible to make measurement in a single exposure if the CCD images are sufficiently corrected for flat field.

Presently we use a disperser that disperses in one dimension. However we anticipate that the technique may eventually be used with dispersers such as echelle grating spectrometers that disperse in two dimensions and have the advantage of wide bandwidth.

The disperser initially used for our prototype was a conventional 0.6 meter spectrometer (Jobin-Yvon HR640) shown in Fig. 1. This had the advantages of adjustable slit width and center wavelength, but was not especially fast (f/8), compact or efficient. Presently, we are substituting for our disperser a high efficiency (80% for unpolarized) volume phase holographic grating, having 90 nm

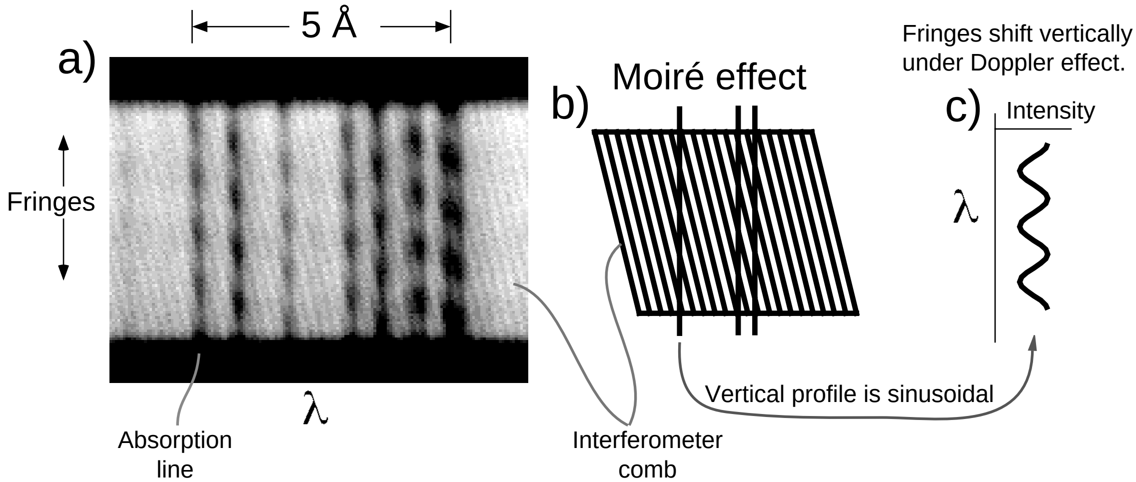

Figure 2. a) Snippet of fringing spectrum when slits are narrow so that underlying interferometer comb can be resolved. b) is model, showing moire effect between absorption lines and interferometer comb, which creates vertically sinusoidal fringes c).

bandwidth, fast f/1.8 optics and very compact size (0.008 m^3). With this disperser the overall instrument could be made the size of a TV-set, and portable. The prototype instrument was assembled rapidly from off the shelf components for a few thousand dollars (outside of the CCD detector). This is in contrast with current radial velocity spectrometers such as the Keck HIRES spectrometer, which cost several million dollars and are the size of a kitchen. Their high cost is due to the need for structural rigidity between the massive optical components spaced at large distances. In contrast, the key component of the fringing spectrometer is the interferometer, which has optical components spaced only a few mm from each other.

3. Fringing spectroscopy technique

The fringing spectrometer technique is based on the moire effect. This occurs between the fringe comb generated by the interferometer and the absorption or emission lines of the source. A small segment of a fringing spectrum is shown in Fig. 2a, taken with slits narrow enough to resolve the interferometer comb. As modeled in Fig. 2b, the overlay of the comb with the solar absorption lines creates moire fringes having sinusoidal character in the direction along the slit (Fig. 2c). Essentially, the moire effect heterodynes the high spatial frequencies of the spectrum (which contain the Doppler shift and lineshape asymmetry information) to low spatial frequencies which are resolved by the disperser. The "carrier" frequency, which is the underlying interferometer comb, needs to be filtered away to reveal the moire fringe. Low pass filtering can be accomplished numerically, or optically by using wider spectrometer slits. Fig. 3 shows a fringing spectrum taken with wider slits showing the moire fringes without resolving the underlying interferometer comb. The use of wider slits has the advantage

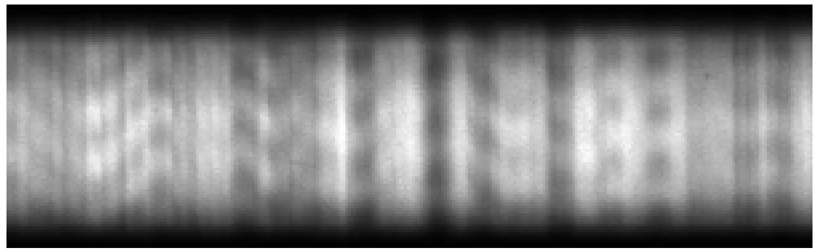

Figure 3. A snippet of fringing spectrum measured when slits are wide so that underlying interferometer comb is not resolved, showing the moire fringes.

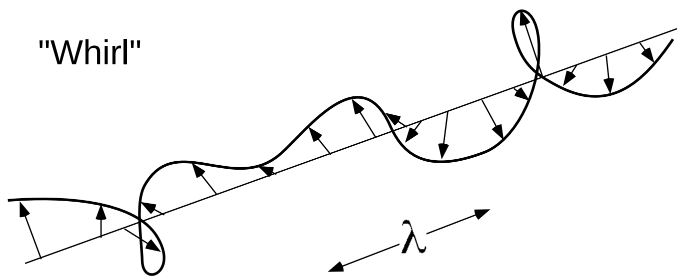

Figure 4. A "whirl" is a meandering vector versus wavelength that describes the moire fringe phase and amplitude, and is the fundamental data format for our technique during analysis. Under a Doppler shift the starlight whirl component rotates relative to the iodine whirl component.

of increasing the flux for blurry sources, although it can diminish the fractional fringe amplitude. Because these are competing effects, the optimum slit width will depend on the etendue presented by the source and the mean feature to feature distance in the spectrum.

The fundamental format of the spectra used for analysis is a vector versus wavelength channel, which we call a "whirl" (Fig. 4), where each vector describes the moire fringe phase and amplitude. Let us denote the reference spectrum "iodine", and the source "starlight" regardless of their true nature. Basis whirls, which are whirls of the starlight alone, and the iodine alone illuminated by featureless white light, are measured separately. Then for each velocity datum the starlight is measured through the iodine vapor cell so that the net whirl contains both stellar and iodine components. The change in rotation of the starlight whirl component relative to the iodine whirl yields the change in Doppler velocity after scaling (14 km/s per cycle).

4. Preliminary results

In order to measure the noise floor of our instrument we desire a velocity source that is clean on a 1 m/s scale. Sunlight has the problem of fluctuating with 1–2 m/s amplitude due to its 5-minute photosphere oscillations. Instead, we use the bromine absorption spectrum (backlit by incandescent light) over a 12 nm

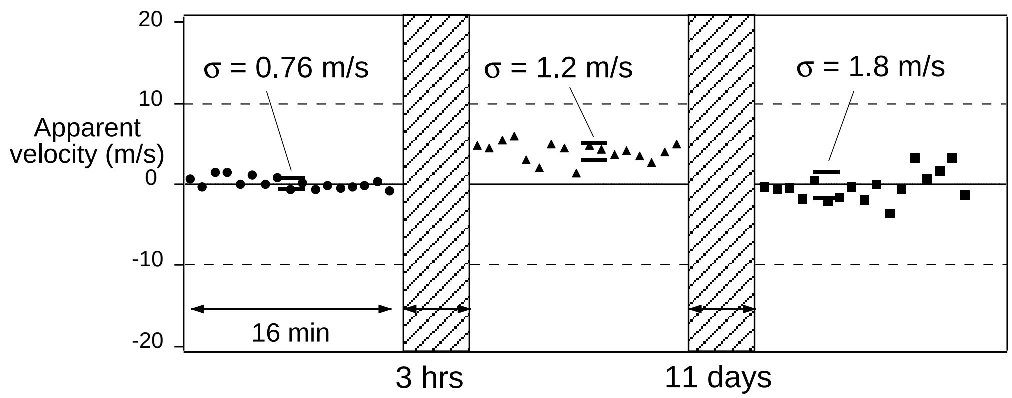

Figure 5. Noise floor test using bromine vapor back lit by white light as a stationary source that is quiet on a 1 m/s scale. Three 16 minute data sets were taken, with flux per datum estimated at 5.2 (circles), 4.6 (triangles) and 3.5 x10^9 (rectangles) photoelectrons. For all sets the vertical axis zero refers to the average velocity of the first set, and the bromine and iodine basis whirls were from the first set. Short term repeatibility was 0.76 m/s, which we estimate is dominated by photon noise. After 3 hours, a zero point drift of 4 m/s is evident. Future stabilization of interferometer cavity should improve this.

bandwidth. This is sufficiently distinct from the iodine absorption spectrum, used as reference. Figure 5 shows that during the first 16 minutes the apparent velocity of the stationary bromine source is measured with a repeatability of 0.76 m/s. In the first 16 minute data set approximately 5x10^9 photoelectrons were used for each velocity datum, distributed over 2500 x 63 pixels in the wavelength and slit directions, respectively. The fluxes were 4.6 and 3.5x10^9 photoelectrons in the next data sets, taken 3 hours, and another 11 days later, but still using basis whirls of the first set. From Monte Carlo simulations we conclude that the observed velocity scatter for the first data set is dominated by photon noise and that therefore the instrumental component could be several times smaller than 0.76 m/s. How much smaller is difficult to assess accurately until we can repeat the measurement with much higher flux. This level of noise compares very favorably with the instrumental noise of the Lick Observatory and Keck HIRES spectrometers, which we infer from Butler's report (1996) to be $\simeq$2 m/s. (They report seeing 3 m/s total error with a calculated 2 m/s photon noise contribution, and we assume the errors subtract in quadrature.) However, a strict comparison is unfair at this preliminary stage since the instruments are observing different sources under different conditons.

The second and third data sets of Fig. 5 taken after 3 hours and again at 11 days shows a zero point drift of not more than 4 m/s. This is already competitive compared to the 3–13 m/s typical errors of fully matured traditional spectrometers, in spite of the lack of environmental controls in our prototype, which consisted of bare optics on an optical table. We made no effort to prevent air convection, stabilize the cavity length, nor regulate temperature and pressure of the bromine vapor, which also effects the result through the variation of its absorption depth. In similar conditions we have observed the unstabilized interferometer cavity to wander as much as 1 fringe over 2 minutes. Thus it is remarkable that the prototype's zero point drift is already competitive with traditional spectrometers where the environment is more controlled. Improvements to the apparatus are now being made which should diminish this drift, including active stabilization of the cavity length and increasing the disperser bandwidth sevenfold to 90 nm.

5. Conclusions

Our interest up until now has been simply to verify the fundamental mathematics of the fringing spectroscopic technique and postpone for the moment the other important issues of long term stability and light efficiency. The low short term velocity noise we demonstrated in our bromine repeatibility tests confirms that the fundamental mathematics is sound. Now we are turning our attention to the latter two issues and preparing the instrument for tests on starlight. We are optimistic that these tests will demonstrate superior advantages of using spectrally multiplexed interferometry to measure broadband Doppler shifts to the 1 m/s level and beyond. At the minimum, the instrument's lower cost and portability facilitates the participation of smaller institutions in the extrasolar planet Doppler survey, and its very large etendue allows use at sites having less than ideal atmospheric seeing conditions, or at telescopes designed to provide low cost but blurry stellar images.

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