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FIXED DELAY INTERFEROMETRY FOR DOPPLER EXTRASOLAR PLANET DETECTION

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ABSTRACT

We present a new technique based on fixed delay interferometry for high-throughput, high-precision, and multiobject Doppler radial velocity (RV) surveys for extrasolar planets. The Doppler measurements are conducted by monitoring the stellar fringe phase shifts of the interferometer instead of absorption-line centroid shifts as in state-of-the-art echelle spectroscopy. High Doppler sensitivity is achieved through optimizing the optical delay in the interferometer and reducing photon noise by measuring multiple fringes over a broad band. This broadband operation is performed by coupling the interferometer with a low- to medium-resolution postdisperser. The resulting fringing spectra over the bandpass are recorded on a two-dimensional detector, with fringes sampled in the slit spatial direction and the spectrum sampled in the dispersion direction. The resulting total Doppler sensitivity is, in theory, independent of the dispersing power of the postdisperser, which allows for the development of new-generation RV machines with much reduced size, high stability, and low cost compared to echelles. This technique has the potential to improve RV survey efficiency by 2–3 orders of magnitude over the cross-dispersed echelle spectroscopy approach, which would allow a full-sky RV survey of hundreds of thousands of stars for planets, brown dwarfs, and stellar companions once the instrument is operated as a multiobject instrument and is optimized for high throughput. The simple interferometer response potentially allows this technique to be operated at other wavelengths independent of popular iodine reference sources, being actively used in most of the current echelles for Doppler planet searches, to search for planets around early-type stars, white dwarfs, and M, L, and T dwarfs for the first time. The high throughput of this instrument could also allow investigation of extragalactic objects for RV variations at high precision.

Subject headings: instrumentation: interferometers — planetary systems — techniques: radial velocities

1. INTRODUCTION

Interferometer techniques based on variable optical delays have already been proposed for high-precision radial velocity (RV) measurements (Connes 1985; Frandsen, Douglas, & Butcher 1993; Douglas 1997), the most recent of which is Holographic Heterodyning Spectroscopy. To our knowledge, none of these techniques has yet achieved RV precision on par with cross-dispersed echelle spectroscopy (∼3 m s^{-1}; Butler et al. 1996). The fundamental limitation of interferometric techniques is the narrow bandpass (e.g., ∼30 Å) compared to the broadband operation of the echelle (∼1000 Å), which provides ∼6 times higher Doppler error than the echelles at the same spectral resolution.

The narrow-band limitation can be overcome by a new kind of interferometer approach based on a fixed optical delay and a postdisperser. Fixed delay interferometers with narrow bandpasses have been used in high-precision RV measurements in solar astrophysics since the 1980s (Title & Ramsey 1980; Harvey et al. 1995; Kozhevatov, Kulikova, & Cheragin 1995, 1996). The best RV precision of ∼3 m s^{-1} has been reported with solar observations (Kozhevatov et al. 1995, 1996). Recent laboratory work with a wide-angle Michelson interferometer with a fixed delay and a medium-resolution grating postdisperser appears to offer ∼1 m s^{-1} RV precision, similar to echelle spectroscopy (Erskine & Ge 2000). The first light of a prototype instrument based on this concept at the Hobby-Eberly 9 m and Palomar 5 m telescopes in 2001 demonstrates that ∼8 m s^{-1} RV precision has been achieved with stellar observations (Ge et al. 2001; van Eyken et al. 2001; Ge, van Eyken, & Mahadevan 2002). Here we present the theoretical principle behind this new RV technique, its performance comparison with the cross-dispersed echelle technique, and its new capability for all-sky RV surveys for extrasolar planets.

2. PRINCIPLE OF FIXED DELAY INTERFEROMETRY

This new approach is illustrated in Figure 1. The circular incoming beam from a telescope is converted to a rectangular one by cylindrical optics, split into two beams with equal amplitude, and fed to an interferometer with a fixed optical delay in one of the arms to form fringes in stellar absorption lines. The uncorrelated fringes over a broad band (*white fringes*) are separated by a postdisperser and recorded on a two-dimensional detector array with fringes sampled on the slit spatial direction and the spectrum sampled in the dispersion direction. This postdisperser can be any dispersing device (e.g., grating, prism, grism, Fabry-Perot interferometer). The fringe period in the slit spatial direction is proportional to wavelength. Therefore, fringes over a bandwidth similar to, or larger than, that of echelles can be properly sampled and measured on a suitable detector array (e.g., CCD), which can help reduce RV measurement noise due to photon statistics.

In this interferometer, high-contrast interference fringes are formed when the optical path difference is within the coherence length (Goodman 1985). Parallel fringes are created when the faces of the two interferometer mirrors are slightly tilted with respect to each other. The interference order, m, is determined by

$$m\lambda = d, \tag{1}$$

where d is the total optical delay and λ is the operating wavelength. Once the delay is fixed, Doppler RV motion will shift the fringes to different orders. The corresponding Doppler ve-

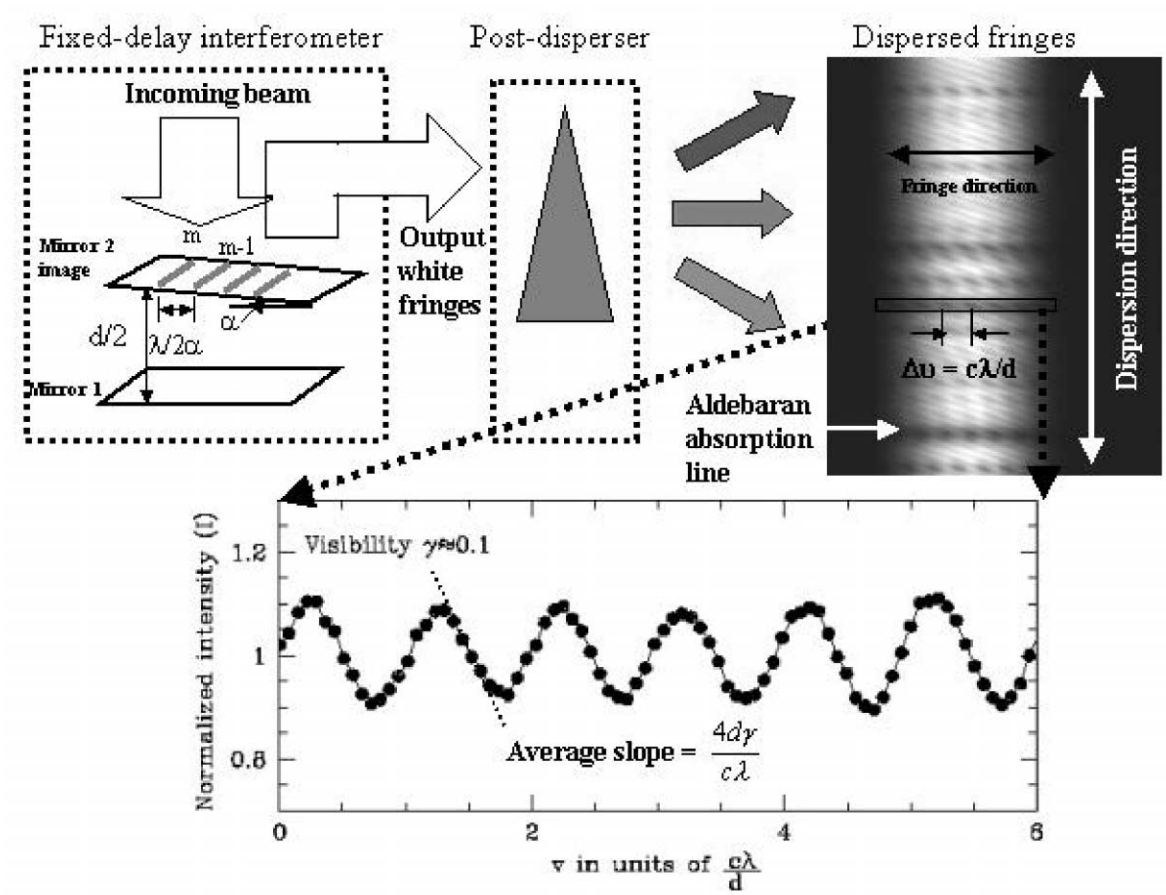

FIG. 1.—Principle of a fixed delay interferometer and a postdisperser. Fringe data were taken with a prototype instrument called the Exoplanet Tracker and a 1000 × 1000 CCD array, developed at Pennsylvania State University (Ge et al. 2001; van Eyken et al. 2001). Stellar interference fringes, formed by a Michelson-type interferometer with ∼7 mm optical delay, lie in the horizontal direction and are sampled by ∼60 pixels. Fringes over different wavelengths are separated by a first-order diffraction grating with a resolving power of $R\sim 6000$, a factor of 10 times lower than typical echelle spectrographs, and are recorded in the vertical direction of the CCD.

locity shift, Δv, is

$$\Delta v = \frac{c\lambda}{d}\,\Delta m. \tag{2}$$

The Doppler analysis is performed on the “normalized” fringe (i.e., divided by the continuum), which can be represented as a function of velocity:

$$I = 1 + \gamma_i \sin\left(2\pi \frac{v}{c\lambda/d} + \phi_0\right), \tag{3}$$

where γ_i is the fringe visibility and ϕ_0 is the phase value for the first pixel of the fringe. Along the fringe, the average uncertainty in the velocity from one pixel is

$$\sigma_p = \left\langle \frac{\epsilon_I}{dI/dv} \right\rangle \approx \frac{c\lambda}{4\,d\gamma_i(\mathrm{S/N})}, \tag{4}$$

where ϵ_I is the uncertainty in the residual intensity at the pixel; for a normalized spectrum $\epsilon_I = 1/(\mathrm{S/N})$, where S/N is the signal-to-noise ratio at the pixel, and the average slope over one side of the fringe (half period) of the sinusoidal interferometer response

$$\left\langle \frac{dI}{dv} \right\rangle = \frac{4\,d\gamma_i}{c\lambda} \tag{5}$$

is used. If an interference fringe is sampled by N_{pix} pixels, then the total intrinsic Doppler error under photon noise limits is

$$\sigma_{f,i} \approx \frac{c\lambda}{4\,d\gamma_i\sqrt{F_i}}, \tag{6}$$

where $\mathrm{S/N} = \sqrt{N_{\mathrm{ph}}}$ is applied, N_{ph} is the number of photons received by each pixel, and $F_i = N_{\mathrm{pix}}N_{\mathrm{ph}}$ is the total photon number collected by each fringe. It is clear that the Doppler precision in the interferometer approach is determined by delay, visibility, and total photons collected in each fringe. If we simply assume that each stellar intrinsic absorption line is a Gaussian shape with an FWHM of $\Delta\lambda_i$ and a depth of D_i $(0 \le D_i \le 1)$, then the visibility as a function of optical delay can be derived (Goodman 1985) as

$$\gamma_i = D_i e^{-3.56 d^2/l_c^2}, \tag{7}$$

where $l_c = \lambda^2/\Delta\lambda_i$ is the coherence length of the interferometer beam. A simple derivation shows that $d\gamma_i$ reaches a maximum value of $0.23 D_i l_c$ when $d = 0.37 l_c$ as shown in Figure 2. There-

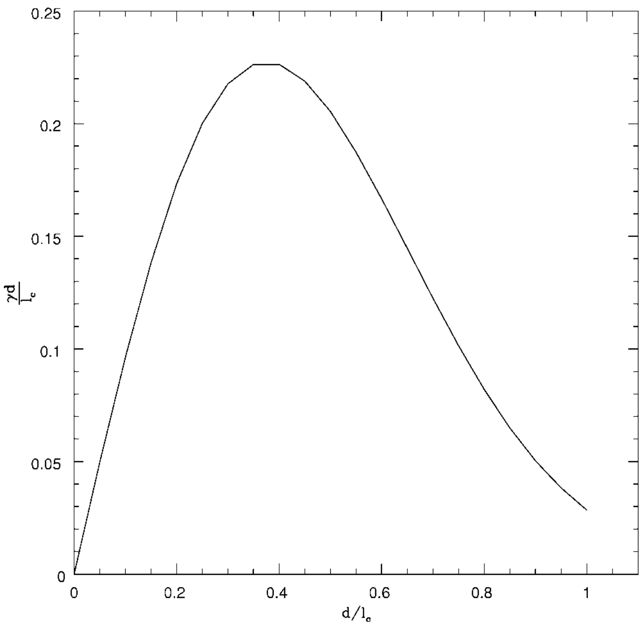

FIG. 2.— Product of delay and fringe visibility vs. delay in the interferometer for a Gaussian-shaped profile. Maximum for $d\gamma = 0.23D_i l_c$ is at $d = 0.37 l_c$. Optimal value for delay depends on the shape of the stellar line profile.

fore, the minimum intrinsic Doppler error per fringe is

$$\sigma_{f,\,i} \approx \frac{1.1c\lambda}{D_i l_c \sqrt{F_i}}. \tag{8}$$

This formula indicates that the intrinsic Doppler error for each fringe decreases with increasing coherence length of the light, the flux per fringe, and the increasing absorption-line depth. If multiple fringes (N_i) over a broad band are used for Doppler RV measurements, then the total Doppler error is

$$\sigma_{f,\,i,\,t} \approx \frac{1}{\sqrt{N_i}} \frac{1.1c\lambda}{D_i l_c \sqrt{F_i}}, \tag{9}$$

assuming line depths, widths, and F_i are the same for all fringes. For the multiple fringe measurements, the intrinsic line profiles are convolved with the response of the postdisperser, which affects RV precision. Assuming that the postdisperser response profile is approximately a Gaussian function with an FWHM of $\Delta\lambda_g$, the FWHM of the observed line is $\Delta\lambda_o \approx \Delta\lambda_g$ if $\Delta\lambda_g \gg \Delta\lambda_i$\. The observed absorption-line depth is

$$D_o \approx \frac{\Delta\lambda_i}{\Delta\lambda_o} D_i. \tag{10}$$

The observed flux within each fringe (or absorption line) is increased to

$$F_o \approx \frac{\Delta\lambda_o}{\Delta\lambda_i} F_i. \tag{11}$$

The total measured Doppler error per fringe becomes

$$\sigma_{f,\,o} \approx \left(\frac{\Delta\lambda_o}{\Delta\lambda_i}\right)^{1/2} \sigma_{f,\,i}. \tag{12}$$

The Doppler sensitivity for each fringe is decreased because of the use of the postdisperser. However, if the detector dimension in the dispersion direction and the sampling of each resolution element are fixed, then the total number of absorption lines covered by the array, N_o, increases to

$$N_o \approx \frac{\Delta\lambda_o}{\Delta\lambda_i} N_i, \tag{13}$$

if the absorption-line density is approximately constant over the wavelength coverage. Therefore, the total Doppler error,

$$\sigma_{f,\,o,\,t} \approx \frac{1}{\sqrt{N_o}} \frac{1.1c\lambda}{D_o l_c \sqrt{F_o}} \approx \sigma_{f,\,i,\,t}, \tag{14}$$

is independent of the resolution of the postdisperser, which is significantly different from the echelle approach and offers new possibilities for Doppler planet searches.

In cross-dispersed echelle spectroscopy, the total measured Doppler error (photon noise error) for a stellar absorption line with an intrinsic FWHM $\Delta\lambda_i$ and depth D_i at a spectral resolution of $\Delta\lambda_o$ is described as

$$\sigma_{e,\,o} \approx \left(\frac{\Delta\lambda_o}{\Delta\lambda_i}\right)^{3/2} \frac{c\Delta\lambda_i}{D_i \lambda \sqrt{F_i}} = \left(\frac{\Delta\lambda_o}{\Delta\lambda_i}\right)^{3/2} \sigma_{e,\,i}, \tag{15}$$

where $\Delta\lambda_o = (\Delta\lambda_e^2 + \Delta\lambda_i^2)^{1/2}$, $\Delta\lambda_e$ is the FWMH of the echelle response. For a fixed bandwidth of the echelle, e.g., ~1000 Å determined by the bandwidth of iodine absorption in the visible for calibrations (Butler et al. 1996), the total measured echelle error is

$$\sigma_{e,\,o,\,t} \approx \left(\frac{\Delta\lambda_o}{\Delta\lambda_i}\right)^{3/2} \sqrt{\frac{N_i}{N_e}} \sigma_{e,\,i,\,t} \approx \left(\frac{\Delta\lambda_o}{\Delta\lambda_i}\right)^{3/2} \sqrt{\frac{N_i}{N_e}} \sigma_{f,\,o,\,t}, \tag{16}$$

where the total number of stellar lines covered in this band, N_e, is fixed. This indicates that the Doppler error in the echelle approach strongly depends on the echelle resolving power. At typical echelle resolution, such as $R \sim 60{,}000$ (e.g., Suntzeff et al. 1995; Vogt et al. 1994; D'Odorico et al. 2000), the Doppler error is ~1.3 times higher than that in the interferometer approach for the same wavelength coverage and photon flux. Therefore, in order to approach the highest possible Doppler precision, approximately the same as that in the interferometer approach, limited only by the stellar intrinsic line profiles, the spectral resolving power must be much higher than the stellar intrinsic line width, i.e., $\Delta\lambda_e \ll \Delta\lambda_i$.

3. DISCUSSIONS

The independence of Doppler sensitivity with the postdisperser resolving power in the interferometer approach potentially allows about 2–3 orders of magnitude improvement in RV survey speed for planets over echelle techniques. The use of low-resolution but high-efficiency postdispersers can significantly boost the overall detection efficiency and allow single-dispersion–order operations for potential multiple-object observations. The current echelle instruments are limited to a few percent total detection efficiency or less; this includes telescope transmission, slit loss, and spectrograph and detection loss due to use of very high resolution echelle and complicated camera optics (Vogt et al. 1994; Suntzeff et al. 1995; D'Odorico et al. 2000). An interferometer coupled with a low-resolution dispersing instrument potentially offers perhaps ∼30% detection efficiency, 5–10 times higher than the echelle, thus allowing us to extend RV survey depth to fainter objects with a fixed size telescope. This high efficiency can be achieved because both the interferometer and the low-resolution spectrograph can be optimized for high transmission.[1] The potential operation of the instrument in multiobject mode allows simultaneous observations of hundreds of objects in a single exposure with broadband coverage on a large two-dimensional detector array. Full-sky coverage of an RV survey for planets becomes possible with a wide-field telescope.

In addition, the simple response function potentially offers lower systematic errors than echelle approaches. Currently, the systematic errors associated with the echelle instrument response account for about 2 m s^{-1} Doppler error, largely due to the deconvolution of observed stellar spectra to create star templates (Butler et al. 1996; J. Valenti 2000, private communication). Since this process is not required in this interferometer approach, the systematic error can be well below 2 m s^{-1}. Hence, Doppler precision of lower than 1 m s^{-1} is potentially reachable through increasing photons collected by each fringe and increasing wavelength coverage. We have achieved ∼8 m s^{-1} Doppler precision with starlight at the Hobby-Eberly Telescope, with ∼140 Å wavelength coverage, an $R = 6700$ postdisperser, and S/N ∼ 100 pixel^{-1}. This error is consistent with the photon noise limit.[2]

[1] For instance, a Michelson-type interferometer with corner cube mirrors can feed both interferometer outputs to the detector at ∼90% efficiency (W. Traub 2002, private communication). A low-resolution spectrograph using a volume phase grating can potentially reach ∼70% transmission (Barden et al. 2000). Together with the telescope transmission (∼80%), fiber feed transmission (∼70%), and detector quantum efficiency (∼90%), the total detection efficiency can reach ∼30%. Details about the total transmission budget will be discussed in a follow-up paper (Ge et al. 2002).

[2] The reason that we were not able to reach higher precision is that the calibration error from using an iodine reference is ∼7 m s^{-1}, dominating the total measurement error. At $R \sim 6700$, mean fringe visibility for iodine absorption lines is too low (∼2.5%) compared to that for stellar absorption lines (∼7%). In the future, a calibration source with much higher fringe visibility will replace the iodine in order to achieve a lower than 1 m s^{-1} precision. Details on new calibration techniques will be reported in the follow-up paper (Ge et al. 2002)

Another exciting possibility with this interferometer technique is to extend RV surveys for planets in wavelengths other than the visible, previously not covered by echelle surveys. Since the interferometer response is simple and stable, there is no need to calibrate instrument responses, as in echelle spectroscopy. Instrument wavelength calibrations (or instrument zero-velocity drift measurements) can be conducted with reference sources with a lower line density than the iodine used in the echelle. Therefore, this instrument can be easily adapted to other wavelengths for maximizing the photon flux and the number of stellar absorption lines for precision Doppler RV measurements. The candidate stars for this potential survey include late M, L, and T dwarfs, early-type B and A stars, and white dwarfs. Late M, L, and T dwarfs have peak fluxes in the near-IR. For instance, the late M dwarfs have peak flux in the near-IR, at least a factor of 10 higher than in the visible (Kirkpatrick et al. 1993, 1999), and since a number of molecular absorption lines are concentrated in this wavelength region, observing time can be significantly reduced if the IR spectra can be used for RV measurements. A and B main-sequence stars have very broad intrinsic absorption lines, dominated by the Balmer series, due to rapid rotation. White dwarfs have very broad intrinsic absorption lines due to pressure broadening. Typical rotation velocity for normal A- and B-type stars is about 150 km s^{-1}, ∼30 times faster than a typical late-type star (Gray 1992; Dravins 1987). Owing to the broader intrinsic line profile, the intrinsic Doppler error for these stars increases by ∼6 times compared to the late-type stars. However, with deep Balmer absorption lines over large wavelength coverage of most of the Balmer lines and high S/N data, it is possible to achieve about a few meters per second Doppler precision for detecting planets around these stars for the first time.

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