Scientific Frontiers in Research on Extrasolar Planets
ASP Conference Series, Vol. Vol. 000, 2003
D. Deming & S. Seager, eds.

All Sky Doppler Extrasolar Planet Surveys with a Multi-object Dispersed Fixed-delay Interferometer

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Abstract. Characterization of extrasolar planetary systems requires a radial velocity (RV) survey for planets around hundreds of thousands of nearby stars of all spectral types over next ten years. This survey will be extremely difficult to conduct using current high resolution echelle spectrometer due to its single object observing mode and low instrument throughput. Here we propose to use a high throughput multi-object dispersed fixed-delay interferometer for the survey. This instrument, a combination of a fixed-delay interferometer with a moderate resolution spectrometer, is completely different from current echelle spectrometers. Doppler RV is measured through monitoring interference fringe shifts of stellar absorption lines over a broad band. Coupling this multi-object instrument with a wide field telescope (a few degree, such as Sloan and WIYN) and UV, visible and near-IR detectors will allow to simultaneously obtain hundreds of stellar fringing spectra for searching for planets. The RV survey speed can be increased by more than 2 orders of magnitude over that for the echelles.

A prototype dispersed fixed-delay interferometer has been observed at the Hobby-Eberly 9m and Palomar 5m telescopes in 2001 and demonstrated photo noise limited Doppler precision with Aldebaran. Our recent observations at the KPNO 2.1m telescope in 2002 demonstrate a short term Doppler precision of $\sim$ 3 m/s with η Cas (V = 3.5), a RV stable star and also obtained a RV curve for 51 Peg. (V = 5.5), confirming previous planet detection with an independent RV technique. The total measured detection efficiency including the sky, telescope and fiber transmission losses, the instrument and iodine transmission losses and detector quantum efficiency is 3.4% under 1.5 arcsec seeing conditions, which is comparable to all of the echelle spectrometers for planet detection.

1. Introduction

Since the discovery of 51 Peg B (Mayor & Queloz 1995), the number of known planets has gone up dramatically and today more than 100 such companions are known. Most of these systems have been discovered using high resolution echelle spectrographs. These instruments are routinely achieving a radial velocity (RV) precision of σ = 5-15 m/s and even as low as 3 m/s in the best cases (Butler et al. 1996; Baranne et al. 1996; Vogt et al. 2000). The echelle spectrographs themselves are large and expensive, with a complicated point spread function which has to be modeled appropriately. The high resolution along with the large wavelength coverage is paid for by the huge costs, the complexity of the instrument and the low throughput of around 1-4% (Vogt et al. 2000; D'Odorico et al. 2002). The observational challenge now lies in detecting as many planetary systems as possible to understand the statistical distribution of planetary masses and distances from the host star. Detecting a large sample of planets will also help in understanding the physical processes underlying planetary formation. A larger sample of stars needs to be surveyed with velocity precision less than 10 m/s to make this possible. Such a task will need large amounts of time on telescopes with current echelles and this is a significant challenge. The next generation of RV survey instruments must have higher efficiencies, should be able to do multi-object RV surveys and should extend the wavelength range to near IR and near UV. The development of our instrument, a multiple object dispersed fixed-delay interferometer, a new generation RV instrument, has been driven in part by these needs.

2. Principle and Unique Properties of Fixed-delay Interferometer

The use of a fixed-delay interferometer for Doppler RV measurements is completely different from the current echelle approach. Instead of measuring the absorption line centroid shifts in the echelle approach, the RV is measured through monitoring interference fringe shifts (Ge 2002). The original idea for using a fixed-delay interferometer for high precision Doppler RV measurements was proposed by two groups (Gorskii & Lebedev 1977; Beckers & Brown 1978). This interferometer with a narrow bandpass has been successfully used for very high Doppler precision measurements of the sun ($\sim$ 3 m/s, Kozhevatov et al. 1995, 1996; sub m/s precision for the GONG measurements, Harvey 2002 private communication). The concept of combining of a fixed-delay interferometer with a moderate resolution spectrometer, or a post-disperser, for broad band operations for high precision stellar Doppler measurements was proposed by Dave Erskine at LLNL in 1997. The initial lab experiments and telescope observing with a prototype demonstrated its feasibility (Erskine & Ge 2000; Ge et al. 2002a). A theory for this new instrument concept was developed by Jian Ge (Ge 2002). In this interferometer approach, the instrument response, determined by the two beam interference, is a simple and well-defined sinusoidal function. For comparison, the echelle response is considerably more complex due to the interference among thousands of divided beams from grating grooves.

In a fixed-delay interferometer (FDI), a fixed optical delay, d, is applied to one of the beams. Therefore, the interference happens at very high interference order, m, determined by $m = \frac{d}{\lambda}$, where λ is the operating wavelength. The Doppler RV motion will shift the fringes of stellar absorption lines to neighboring orders. The corresponding Doppler velocity shift is

$$\Delta v = \frac{c\lambda}{d}\Delta m = \frac{c\lambda}{d}\frac{\Delta\phi}{2\pi}, \tag{1}$$

where $\Delta\phi$ is the measured phase shift of a fringe. If the absorption line density is constant over the observed band, then the total observed Doppler error is

$$\sigma_{t,fringe,ob} \approx \frac{1}{\sqrt{N_o}}\frac{1.1c\lambda}{D_o l_c \sqrt{F_o}} \approx \sigma_{t,fringe,I} \tag{2}$$

where N_o is the total number of absorption lines covered by the array, D_o is the observed absorption line depth, $l_c = \lambda^2/\Delta\lambda_I$ is the coherence length of the interferometer beam for a bandwidth of $\Delta\lambda_I$, the intrinsic width of typical stellar absorption lines, F_o is the observed flux within each observed fringe (or absorption line), and $\sigma_{t,fringe,I}$ is the intrinsic Doppler precision at infinite spectral resolution of a post-disperser (see Ge 2002 for details). This indicates that *the Doppler sensitivity of the FDI is independent of the spectral resolving power of the post-disperser*, contrary to echelle spectroscopy. In the echelle, the total observed Doppler error is

$$\sigma_{t,echelle,ob} \approx \frac{1}{\sqrt{N_o}}\frac{1.1c\Delta\lambda_o}{D_o\lambda\sqrt{F_o}} \approx \left(\frac{\Delta\lambda_o}{\Delta\lambda_I}\right)\sigma_{t,echelle,I} \approx \left(\frac{\Delta\lambda_o}{\Delta\lambda_I}\right)\sigma_{t,fringe,ob}, \tag{3}$$

where the observed line FWHM is $\Delta\lambda_o = \sqrt{\Delta\lambda_I^2 + \Delta\lambda_e^2}$, and $\Delta\lambda_e$ is the FWHM of the echelle response, $\sigma_{t,echelle,I}$ is the intrinsic Doppler precision at infinite spectral resolution of an echelle. *The Doppler error in the echelle approach strongly depends on the echelle resolving power and stellar intrinsic line width* (Bouchy et al. 2001; Ge 2002). For a solar type star with absorption lines of FWHM $\sim$ 5 km/s (Dravins 1987), at moderate resolution (such as $\Delta\lambda_o \sim 10\Delta\lambda_I$, or $R \sim 6000$), the echelle approach has $\sim$ 10 times higher Doppler error than the interferometer approach. At high resolution, such as $R \sim 60{,}000$, being used for planet detection (e.g., Vogt et al. 1994; D'Odorico et al. 2000), the Doppler sensitivity for a solar type star is still $\sim$ 1.4 times worse than the interferometer.

The independence of Doppler sensitivity from the post-disperser resolving power in the interferometer approach opens up new possibilities for RV studies. The use of low resolution but high efficiency post-dispersers can significantly boost the overall detection efficiency, dramatically reduce the instrument size and cost and allow single dispersion order operations for multiple object observations. Full sky coverage for an RV survey for planets becomes possible with wide field telescopes. *Multiple object capability is one of the most significant advantages for this interferometer approach.* The simple and stable response function in the interferometer approach leads to potential low systematic errors, which may allow this approach to reach sub m/s Doppler precision.

Another exciting possibility with this interferometer technique is to extend RV surveys to 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 the instrument response in contrast to the echelle; only wavelength calibration is required. Hence, reference sources with a lower line density than the iodine, which is popularly used in the echelle, can be used.

Therefore, this instrument can be easily adapted to other wavelengths, in which more photon flux and stellar absorption lines are available for precision Doppler RV measurements. For instance, late M, L and T dwarfs have peak fluxes in the near-IR. Integration time can be significantly reduced if the IR spectra can be monitored. B and A main sequence stars and white dwarfs have very broad intrinsic absorption lines dominated by the Balmer series. The intrinsic Doppler error for each Balmer line is about the same as that for late type stars. Since there are only a few dozen broad lines that can be used for early type stars while $\sim$ 1000 lines can be used for late types, the overall observed Doppler error is about $\sim$ 10 times higher for the early types than late types for the same S/N data. Since early type stars are usually much brighter in the near UV than late types at the same astronomical distance (e.g. an A star is about 100 times brighter than a G type star in the visible), it is possible to achieve $\sim$ a few m/s Doppler precision by increasing S/N by a factor of $\sim$ 10.

3. Performance of a Prototype Dispersed Fixed-delay Interferometer

In 2000-2001, we developed a prototype dispersed fixed-delay interferometer, called Exoplanet Tracker (ET), similar to an earlier version built by Jian Ge and his collaborators at LLNL (Ge et al. 2002a). The instrument consists of a Michelson interferometer with 7 mm fixed optical path difference, a Czerny-Turner type spectrometer with a 100 mm diameter collimator beam and a 1k$\times$1k Photonics CCD camera with 24 μm pixel size. The first light stellar observations were conducted at the Hobby-Eberly 9 m telescope (HET) in October 2001 (Ge et al. 2002b). The spectral resolution is $R = 6700$. The wavelength coverage is 140 Å with the CCD. The measured Doppler precision is approaching a photon-noise limit as demonstrated by a direct comparison between predicted theoretical RV errors and measured values shown in Figure 1(left). This figure also indicates that the iodine calibration contributes major errors in the measurements due to its very low fringe visibility compared to that for the star.

ET was further tested at the Palomar 5-m telescope in Dec. 2002. Our results demonstrate that multiple object observing is feasible with the interferometer. Figure 1(right) shows two adjacent fringe spectra obtained simultaneously with ET. One fringe data is from Aldebaran. The other is from a ThAr lamp. The two fringe spectra occupy only $\sim$ 1/8 CCD detector area. Therefore, we can simultaneously cover $\sim$ 15 fringe data from 15 stars if multiple stellar beams are available.

A modified version of ET was used for an engineering run at the KPNO 2.1-m telescope in August 2002 before we install a permanent one in 2003 for a long-term survey. The old $f/10$ spectrograph was replaced by an $f/7.5$ spectrograph. The KPNO 1k$\times$3k back-illuminated CCD with 15 μm pixels was used instead of the old 1k$\times$1k CCD. The wavelength coverage has been increased to 270 Å due to the faster instrument focal ratio and larger detector array. An $f/8$ telescope beam is fed into a 200 μm fiber, which matches a 2.5 arcsec stellar image. Due to the focal ratio degradation, the output focal ratio of the fiber is $f/6$, which is converted to $f/7.5$ to feed the spectrograph. The spectrograph entrance slit width was dialed to about 180 μm, which causes about 30% photon loss at the slit. The FWHM of each absorption line is sampled by 12 pixels. Under

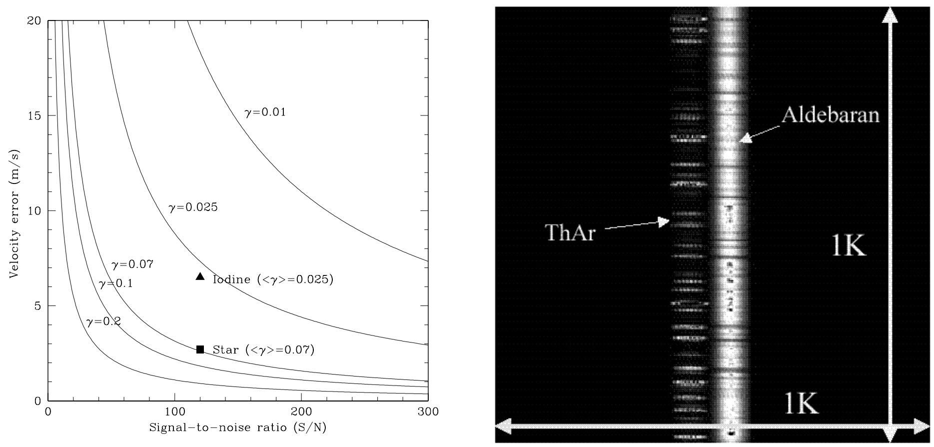

Figure 1. Left: Doppler velocity error vs. S/N. The solid lines represent theoretical relations between RV error and S/N for different fringe visibility, derived from Eq. (2). The filled square marks a point for the measured error for a bright star, Aldebaran. The filled triangle represents the measured iodine error. Right: Two fringing spectra, one for Aldebaran and the other for ThAr lamp, were simultaneously obtained with the ET and the CCD at the Palomar 5m in December 2001, demonstrating its capability for multiple object observations.

1.5 arcsec seeing conditions, the total instrument throughput including the sky, telescope transmission, fiber loss, instrument and iodine cell transmission and detector quantum efficiency is 3.4%. This was achieved by feeding only one of the two interferometer outputs into the spectrograph. This allows us to routinely observe stars as faint as V = 7.6 during the whole run. Although the seeing conditions were never better than 1.5 arcsec, we still were able to continually monitor 6 stars (Arcturus, η Cas, υ And, 51 Peg, 31 Aql, and HD 209458) over 8 nights when sky was relatively clear.

Part of the data have been reduced. Figure 2(left) shows a velocity curve for η Cas within an hour. The measured RV values well match the predicted ones caused by the Earth's motion. The RMS residual from this measurement indicates a Doppler precision of 2.9 m/s in a short period. Measurements from several other nights indicate we have reached a Doppler sensitivity of $\sim$ 3-8 m/s for η Cas. Figure 2(right) shows a RV curve from 51 Peg after Earth's motion is subtracted, superimposed with a predicted curve from previous echelle measurements. Our result is consistent with previous measurements, demonstrating that ET is capable of detecting extrasolar planets. Large long term RV measurement errors are mainly caused by data reduction and also instrument calibration. A better version of data reduction software package is being developed. Better long term RV precision is expected.

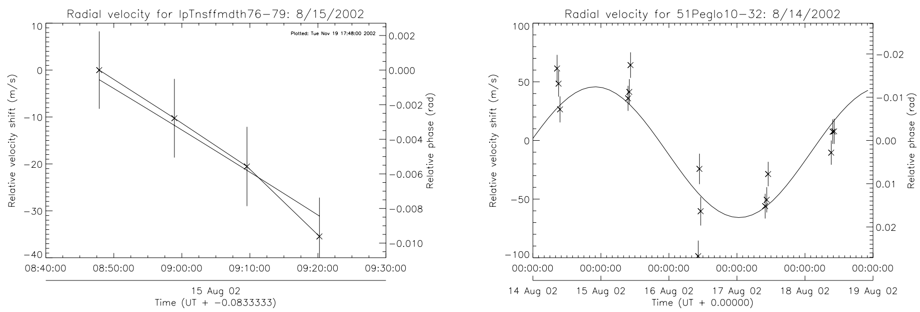

Figure 2. Left: Doppler precision within an hour for Eta Cas with ET. The RMS error is 2.9 m/s. Right: Doppler velocity curve of 51 Peg due to a planet with 4 day period uncovered with ET. The solid line is the expected RV curve from previous measurements with echelle spectrometers. The large RV deviation in the 3rd day is partially due to bad data calibration.

4. All Sky Doppler Surveys for Extra-solar Planets

Observations with ET have demonstrated that the dispersed fixed-delay interferometer is suitable for multiple object observing and can provide high throughput and high Doppler precision. Multi-object and high throughput Doppler surveys are important since they can significantly speed up the detection of extrasolar planetary systems and also reduce the cost. Currently, only about 4000 solar type stars are being searched by half a dozen telescopes using the echelles. Based on current planet detection rate of 10% of solar type stars, $\sim$ 400 planets will be discovered in the next $\sim$ 10 years. These surveys are time-consuming and very costly. This is because current echelles can only measure a single object per exposure, and because only relatively bright stars can be observed since the instrument has low detection efficiency, whereas high photon flux is required for precision measurements. Therefore, a multiple object RV survey can significantly improve the current situation.

Considering there are not many bright stars in the sky for the measurements, the multiple object survey must include relatively faint stars within the telescope field of view (FOV). Based on our estimation from previous star count surveys in the visible (Bahcall & Soniera 1980) and a dust extinction map (Schlegel et al. 1998), we find there are about a half million stars from A – M types brighter than V = 10, and about 4 millions of stars are brighter than V = 12. On average, about 100 stars with V magnitude brighter than 12 mag. are within a 1 deg field-of-the-view. Therefore, in order to conduct an efficient all sky survey for extrasolar planets with a multiple object dispersed fixed-delay interferometer, we need to reach about V = 12 with a wide field telescope.

This all sky survey is possible with modern wide field telescopes such as the Sloan 2.5-m and the WIYN 3.5m telescopes. The Sloan has a 7 degree FOV and the WIYN has a 1 degree FOV. Since both of the telescopes are moderate size, high throughput becomes critical to reach high Doppler precision for faint stars. High throughput can be achieved with an optimally designed instrument.

The prototype at the KPNO 2.1-m has already demonstrated good throughput of 3.4% under 1.5 arcsec seeing. In the future, a factor of 4 times improvement should be achievable, including 2 times in the interferometer transmission by feeding both interferometer outputs to the spectrograph, 1.4 times in the étendu match through updating current spectrograph with a faster spectrograph (e.g., $f/2$ instead of $f/7.5$), and 1.5 times in the spectrograph transmission by using a higher efficiency grating (such as a VPH grating with $\sim$ 85% efficiency instead of current reflection grating with $\sim$ 55% efficiency). A total estimated detection efficiency of $\sim$15% can be expected. With this detection efficiency, a Doppler precision of $\sim$ 15 m/s can be reached for a V = 12 star within an hour integration and $\sim$ 1000 Å wavelength coverage. Therefore, most of the stars brighter than V = 12 can be surveyed with high Doppler precision for planet candidates at 2 m class wide field telescopes with multi-object RV instrument. The candidate systems can be further studied with a single object high throughput dispersed fixed-delay interferometer with higher precision at larger aperture telescopes to look for additional planet members.

In the future, in order to take full advantage of the potential of the multi-object dispersed fixed-delay interferometer for all sky RV surveys, we need to simultaneously feed multi-object fiber beams into three instruments which have best sensitivity in the near-IR, visible and near-UV, respectively. This design allows optimal match of the interferometer sensitivity with the peak of the spectral flux and lines. For instance, a late M type star has about 10 times more flux in the near-IR than in the visible and has many molecular and atomic lines for precision Doppler measurements (Kirkpatrick et al. 1993). Because the line width is very different from early type to very late types, the optical delay will be changed accordingly to minimize Doppler errors.

To fully achieve high Doppler precision with this instrument, a large waveband is very important since this will allow the capture of more photons from stars for the measurements. In the prototype, the wavelength coverage is about 200 Å. By simply increasing wavelength coverage to $\sim$ 1000 Å, more than a factor of 2 times better Doppler precision can result. Doppler precision can be possibly further reduced by using reference sources with higher visibility than the iodine absorption. Our measured fringe visibility for typical Thorium lines in our Palomar data is about 50%, resulting in intrinsic Doppler error well below 1 m/s. Current RV measurements using ThAr calibration in Dr. Mayor's group have already achieved $\sim$ 5 m/s precision and with further improvement such as double fiber mode scrambling and vacuum operation, they believe that they can reach $\sim$ 1 m/s in the new HARPS high resolution echelle spectrometer (Queloz 2002 private communications; Pepe et al. 2000). We believe we may be able to achieve similar calibration precision by using similar procedures. If this technique works, the observing efficiency can be tripled over that of our current iodine-based technique since there will be no photon loss due to iodine absorption (typical loss by iodine absorption $\sim$ 30-40%) and also there is no need to create a separate stellar template for each observation. This will be a big plus for the survey.

In summary, to have a very successful all sky survey requires multi-object observation capability, high Doppler precision and high throughput. A wide field telescope with at least three multi-object dispersed fixed-delay interferometers optimized for near-UV, visible and near-IR wavebands can provide the best sensitivity for detecting thousands of planets around stars from very early types to very late types in the near future.

Acknowledgments. The authors are grateful to Larry Ramsey, Don Schneider, Eric Feigelson, Steinn Sigurdsson, Tom Soltysinski, Ron Reynolds, Fred Roesler, Didier Queloz, Harvey Moseley, Bruce Woodgate, Roger Angel, Mike Shao, Chas Beichman, Bill Cochran, Wes Traub, Ed Jenkins and Jim Gunn for useful discussions. We acknowledge support from the HET staff, the Palomar observatory staff and KPNO staff. This work is supported by NASA JPL and Penn State Eberly College of Science. A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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