All Sky Extrasolar Planet Searches with Multi-Object Dispersed Fixed-delay Interferometer in Optical and near IR

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Abstract

An all sky survey for extrasolar planets with wide field telescopes, Sloan 2.5m and WIYN 3.5 telescopes, is being developed. This survey will use a multi-object version of current Exoplanet Tracker (ET) Doppler instrument commissioned at the KPNO 2.1m telescope in June 2004. This instrument is based on dispersed fixed-delay interferometer, a combination of a Michelson interferometer with a moderate dispersion spectrometer (Ge 2002). This custom designed instrument (f/2 optics) has a wavelength coverage of ~ 600 Å with a 4kx4k CCD camera at a spectral resolution of R = 5,000. The measured instrument detection efficiency, including telescope, fiber, interferometer, spectrometer and detector losses, has ~ 18% (or 50% throughput from the fiber input to the detector), more than 4 times higher than current echelle instruments being used for planet detection.

ET has been able to routinely obtain S/N ~ 80 data for V ~ 8 mag. stars in 15 min exposures with the KPNO 2.1m. It allows us to reach ~ 3.5 m/s Doppler precision for radial velocity (RV) stable stars with S/N ~ 120 per pixel. It also allows us to confirm an exoplanet curve of HD 130322 (V = 8.05) with rms Doppler error of 12.3 m/s (preliminary results). We are in the middle of design of two prototype multiple object RV instrument for the Sloan and WIYN telescopes, which are capable of observing 50 stars (V ~ 8–13) in a single exposure. We plan to conduct the all sky survey for planets around ~ 1 millions of stars with Sloan starting in 2008. Our goal is to identify ~ 100,000 extrasolar planets with ~ 1,000 solar analogues through this survey.

Key words: interferometer, Doppler, radial velocity, extrasolar planets, wide field telescope, multiple object, spectroscopy

Introduction

Since the first extrasolar planet around a solar type star was detected around 51 Peg in 1995 (Mayor & Quolez 1995), over one hundred of planets have been discovered around nearby bright stars using the Doppler technique with cross-dispersed echelle spectroscopy Most of the stars have V magnitude bright than 8 magnitude and spectral type from late F to early M. Based on current detection rate, the total number of detected planets is expected to be tripled over next 10 years. However, in order to fully understand the

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fundamental physical processes underlying planetary formation, a proper statistical distribution of orbital elements, planetary masses, frequency, planet/star property correlations such as metallicity, and the characterization of multiple-planet systems, we need to detect thousands or more planetary systems. Furthermore, the on-going planet transit surveys using the ground-based telescopes such as OGLE have produced many faint candidate stars with possible transit planets over wide field of views and the future space transit mission such as KEPLER mission will also produce many faint candidates over a ~100 square degree field of view (Konacki et al. 2003, Borucki et al. 2003). These candidates need to have radial velocity follow up to confirm the detection and also measure planet properties such as mass and planet orbital properties.

Current echelle instruments produce velocity accuracies of 2-3 m/s with the best close to 1m/s. However, the instrument throughput is relatively low (less than 20% instrument throughput measured from the spectrograph entrance slit to the detector) and the instrument is designed for single object observations. With the single object and low throughput instruments it is extremely challenging to detect thousands of planets and also confirm thousands of transit planet candidates over next 10 years.

A new Doppler technique based on dispersed fixed-delay interferometry developed by us offers an exciting opportunity to address this challenging issue in Doppler planet searches (Erskine & Ge 2000; Ge 2002; Ge, Erskine & Rushford 2002; van Eyken et al. 2004). This approach 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 in the interferometer approach (Ge 2002). This technique enables high throughput and multiple object Doppler measurements. We have demonstrated its feasibility for detecting planets around faint stars at the Kitt Peak National Observatory 2.1m telescope (van Eyken et al. 2004). We also demonstrated its superior throughput gain over the echelle instruments. For instance, our existing single object instrument has provided about 50% instrument throughput, while the Keck existing High Resolution Echelle Spectrograph (HIRES) provides about 13% instrument throughput (Vogt et al. 1994). The most important property of all is that this instrument can be simultaneously fed with hundreds of faint star light over wide telescope field of views instead of one for the echelle instruments to enable planet survey speed increase by two orders of magnitude. This clear advantage is enabling us to launch an all sky survey for planets around millions of faint stars at wide field telescopes such as Sloan and WIYN telescopes over next 15 years instead of thousands of bright stars which have been monitored by a dozen echelle single object spectrographs at large ground based telescopes since early 1990's.

In the following we describe our all sky planet survey project being developed at the University of Florida, including a multiple object RV instrument configuration, instrument parameters, instrument sensitivity, science goals and preliminary schedule. Our main survey telescope will be the Sloan wide field telescope.

The long term configuration of multiple object RV instrument at wide field telescopes

Our long term all sky survey Doppler instrument configuration will likely consist of an optical dispersed fixed-delay interferometer channel and an IR interferometer channel. Two configurations are being considered: (1) visible and IR channels share common fiber inputs; (2) visible and IR channels have separate fiber inputs. Figure 1 shows the common fiber feed configuration. In this configuration, a total of 400 fibers will be fed into the instrument. A dichroic mirror will reflect the IR light to the IR channel while passing the visible light to the visible channel. The visible channel has a 16kx16k mosaic CCD to

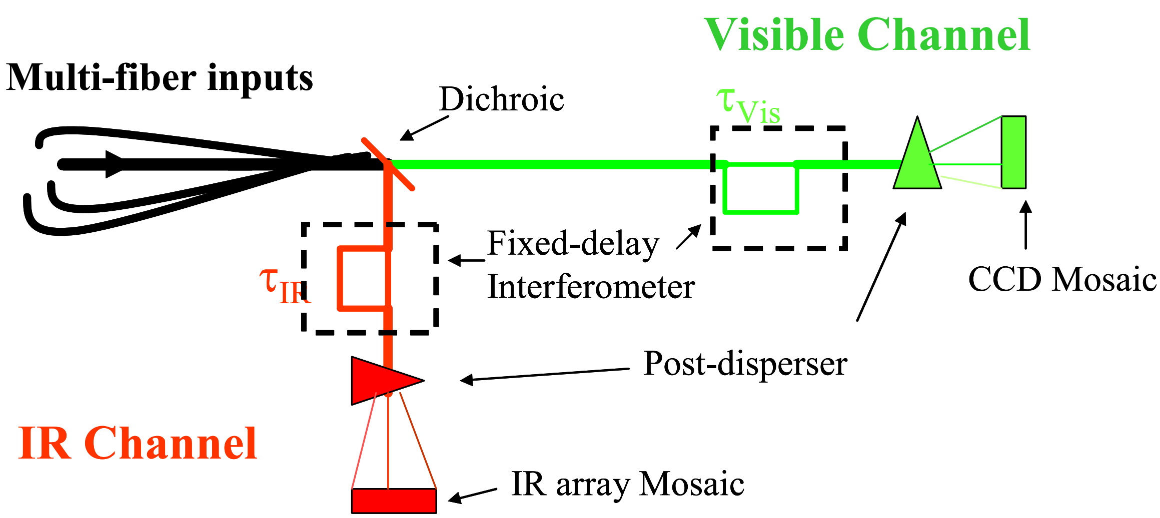

Figure 1. A schematic configuration of a Sloan ET for all sky planet survey starting in 2008.

collect a total of 800 fringing spectra from 400 stars in each exposure within each wide field (each star has two spectra from the two outputs of the interferometer, similar to the current spectral format shown in Figure 2; each spectrum covers 30x8192 pixels and with 10 pixels separation from neighboring spectra). This channel is optimized for searching for short period (a few days) and long period (a few years) planets around stars between F5 and M5 in the visible band (0.4-0.6 μm). Figure 3 shows a preliminary optical design of an optical spectrograph (without a VPH grating installed) that can observe 400 objects with a 16kx16k CCD mosaic.

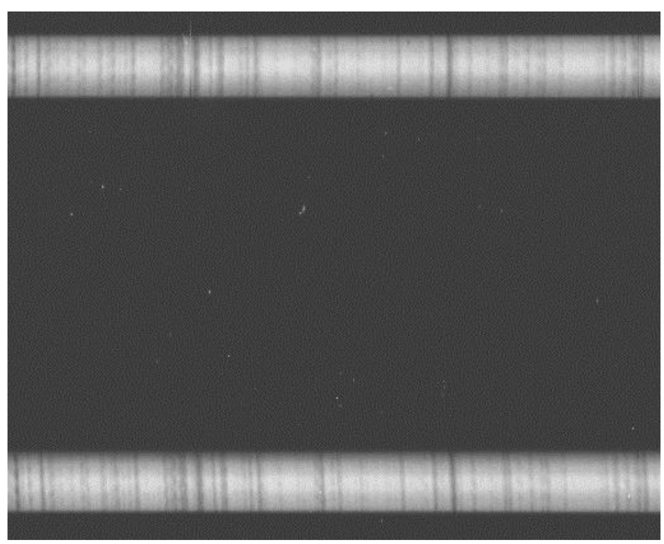

Figure 2. Fringing spectra of a planet candidate star, HD 68988 (V = 8.21), in a 30-min exposure with current ET at KPNO in March 2004. The average S/N ≈ 110 per pixel.

The IR channel has a 4kx4k IR array. It can be upgraded to a larger array when such devices become available. The 4kx4k IR array will cover 100 fringing spectra from 100 stars using a single interferometer output

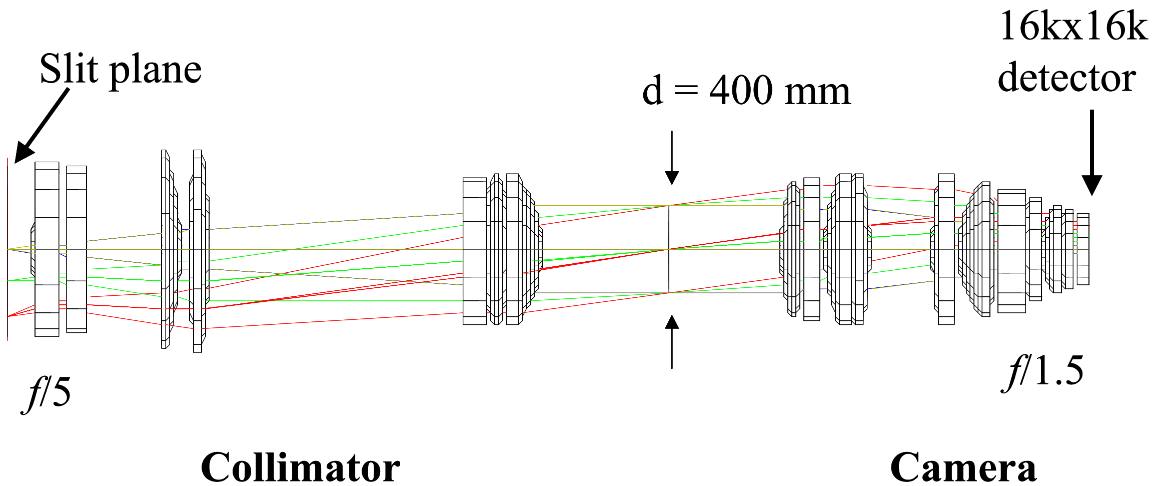

Figure 3. Optical design of a wide-field high-throughput spectrograph with a 16kx16 mosaic CCD camera for the Sloan ET.

feeding. The IR interferometer is optimized for detecting short period and long period planets around stars with spectral types later than M5 in the near-IR band (1.2-1.7μm). These M dwarfs can be more efficiently surveyed in the near-IR since these stars are about 10 times brighter than in the visible (Kirkpatrick et al. 1993). Study of these lower mass stars allows the potential of detection of lower mass planet companions.

The other possible configuration for Sloan ET is the optical channel and IR channel have separate sets of fibers. The number of fibers for each channel is to be determined. The main advantage of this setup is the total throughput may be slightly higher than the common fiber feed configuration. However, the total fiber number for each channel will be significantly less than 400.

Spectral format and wavelength coverage for the visible channel of the Sloan ET

The visible channel of the all sky survey ET has a 16kx16k CCD. Each quadrant of the mosaic (8kx8k) covers 200 fringing spectra from 100 stars, i.e., each fringing spectrum is sampled by 30x8192 pixels. At *f*/1.5, 8k pixels will cover 1700 Å between 4000-6000 Å. This wavelength coverage is scaled from current ET wavelength coverage at the KPNO 2.1m telescope (480 Å at *f*/2 with a spectral resolution of R = 7000 and 3k pixels).

The square arrangement of the CCD detectors will minimize the optical and mechanical size in the spectrograph. The special spectral format on the detector, i.e., 4 sets of 200 stellar fringing spectra on four quadrants, will be realized through inserting two long slits at the spectrograph entrance.

Sensitivity Estimates

Doppler sensitivity of the all sky survey ET is estimated from the measurements of the current KPNO ET, during engineering runs in January, March and June 2004. Figure 2 shows a typical fringing spectrum obtained with ET. The total average detection efficiency from above the atmosphere to the detector was measured to be 17.8% (or the total instrument throughput including the instrument and detector is 50%). For comparison, the newly commissioned HARPS instrument, designed for planet detection, at the ESO 3.6 m telescope has delivered a total detection efficiency of 4% (see web site at http://www.eso.org/gen-fac/pubs/messenger/archive/no.114-dec03/mess-harps.pdf). The estimated total detection efficiency of the Keck HIRES Echelle, which has been used for planet detection, is 2% (Vogt et al. 2000).

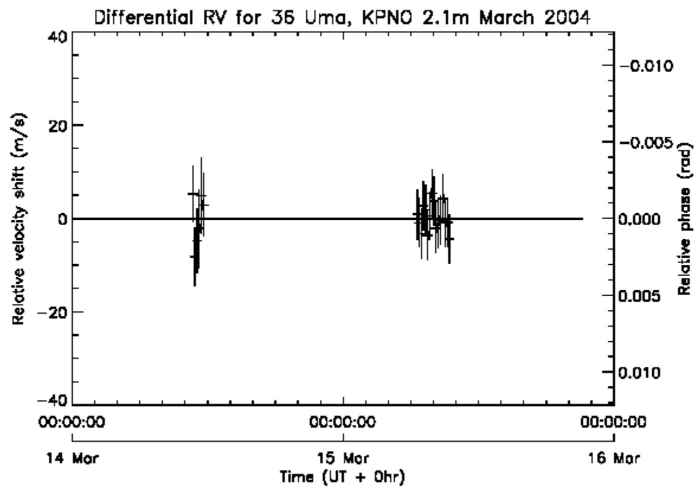

Figure 4. RV curve of the stable star 36 Uma obtained with ET at the KPNO 2.1m in March 2004. The measured short term (two days) stability is 3.6 m/s.

Figure 4 shows the RV measurements of a RV stable star, 36 Uma taken with the KPNO ET instrument and a 1kx3k CCD camera in March 2003. The instrument setup is shown in Figure 5. The overall Doppler stability over two nights is 3.6 m/s; the highest measured Doppler precision is 2.9 m/s (the average S/N is 120 per pixel). This Doppler stability is two times better than we achieved with our prototype ET at the 2.1m in August 2002 (van Eyken et al. 2004). The measured Doppler precision is roughly inversely proportional to S/N, following the theoretical prediction (Ge 2002). Figure 6 shows part of the uncovered Doppler radial velocity curve of HD 130322 (V = 8.05) obtained with ET and a new 4kx4k CCD camera in 15 min exposures at the KPNO 2.1m in June 2004, confirming the detection of a one Jupiter mass planet around this star from a previous survey (Udry et al. 2000). Our Doppler precision (very preliminary, more data is being analyzed) is 12.3 m/s over three days with the best precision of ~ 8 m/s, indicating the instrument is ready for a planet survey at the 2.1m.

Table 1. Doppler radial velocity sensitivity of current KPNO ET and future Sloan ET in an hour exposure

V magnitude	KPNO 2.1m[1]	Sloan 2.5 m[2]
8	4.0 m/s	1.9 m/s
9	6.3 m/s	2.3 m/s
10	10.1 m/s	4.8 m/s
11	16.0 m/s	7.4 m/s
12	25.3 m/s	11.8 m/s
13	40.0 m/s	18.6 m/s

[1]KPNO ET has f/2 spectrograph design, 4k CCD pixels cover 600 Å.
[2]Sloan ET has f/1.5 spectrograph design, 8k CCD pixels cover 1700 Å.

Table 1 lists the expected Doppler sensitivity of the Sloan ET based on current ET performance at the KPNO 2.1m telescope, i.e., 4.0 m/s for a *V* = 8 solar type star in an hour integration. In an hour exposure, the Sloan ET can probably reach better than 20 m/s Doppler precision for *V* < 13. This Doppler precision allows us to uncover more than 90% of extrasolar planets discovered to date with the single object high resolution cross-dispersed echelle spectrographs (see extrasolar planet web site at http://www.obspm.fr/encycl/encycl.html).

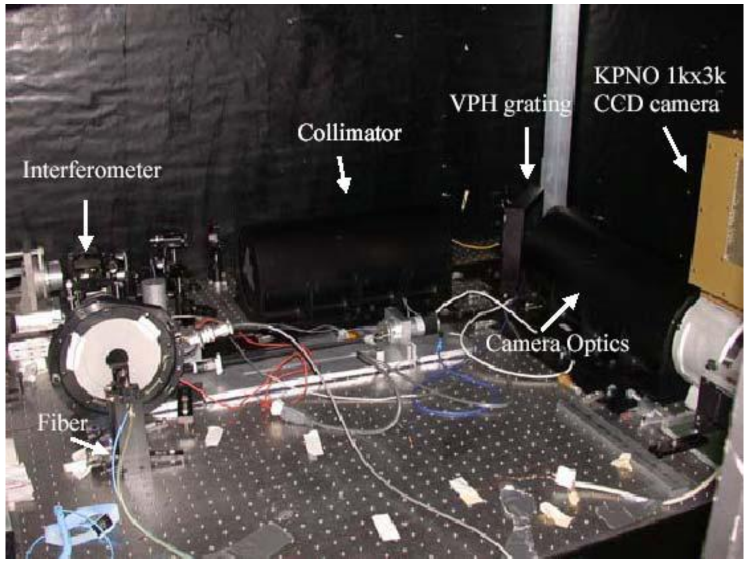

Figure 5. Bench mounted ET at the KPNO 2.1m telescope Coude room in March 2004. The 1kx3k CCD camera has been replaced with a 4kx4k CCD camera in the 2004 June engineering run 2004.

Scientific goals

The Sloan RV survey will cover every field accessible to the northern sky during a 10-year baseline to detect extrasolar giant planets. Based on estimation from previous star count surveys in the visible (Bahcall & Soniera 1980) and a dust extinction map (Schlegel et al. 1998), we find that there are about 2 million stars with $V < 12$ and spectral type between F and M over the entire sky (Table 2) and about 5 million stars with $V < 13$. On average, there are about 100 stars with $V<13$ suitable for the RV survey within a 1 square deg field-of-the-view (FOV). This varies enormous with Galactic latitude. However, at the intermediate latitudes, we expect a total of 400 or more stars with $V<13$ to be available for precision RV measurements within the Sloan 7 square degrees of FOV. Our goal for the visible RV survey over 10 years is to monitor 1 million stars of spectral type between F and M with V= 7-13 over multiple epochs (> 3).

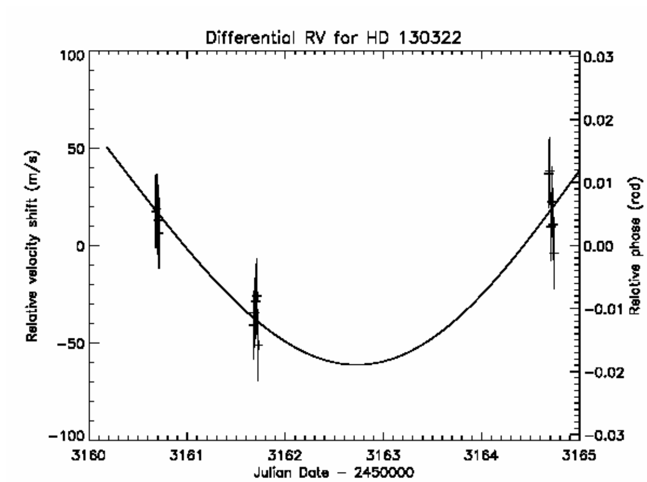

Figure 6, part of the Doppler curve for HD 130322 (V = 8.05), with rms error of 12.3 m/s in 15 min exposures.

Based on the current planet detection rate, ~7-10% solar type stars harboring Jovian planets, we expect to detect ~ 100,000 giant planets at the end of the survey, *over 200 times more planets than the projected planet number from the single object RV surveys with echelle instruments on ~ a dozen ground-based telescopes*. Among ~ 100,000 planetary systems, it is likely we will be able to identify more than 1,000 solar analogues which have a Jupiter-like planet at ~ 5 AU to protect inner terrestrial planets, and also detect ~ 1,000 transit planets for studying atmospheric compositions of these planets.

These systems will be excellent candidates for future Terrestrial Planet Finder (TPF) and post-TPF missions for detecting Earth-like planets in the solar neighborhood. These planetary systems will also allow investigation on planet formation and evolution in different environments; statistical distributions of planet mass, eccentricity, and orbital distance; the correlations between planets and stellar properties such as metallicity, spectral and luminosity types; and characterization of multiple-planet systems.

Spectral Type	$m_v < 10^{th}$	$m_v < 11^{th}$	$m_v < 12^{th}$
A1-A9	292693	756629	1704211
F0-F9	183666	559194	1515384
G0-G9	29864	95083	1309935
K0-K9	5941	22649	81039
M0-M9	149	620	2382
Total counts	**512313**	**1434173**	**3612950**

Table 2. All sky main sequence star counts between spectral type A to M.

We expect to monitor at least a few hundreds of thousands of M and later type stars (brown dwarfs) in the near IR (depending on the detector size). Our goal for the IR survey is to be able to discover Earth-mass planets in the habitable zone of these very low mass stars if such planets exist. Such planets will be quite close to the parent star (~4 day orbit). The luminosity of the star is low, so the temperature (i.e., distance) of the planet is suitable for liquid water quite close to the star. The proximity to the central star means the RV signature is large enough (~ 2 m/s for an Earth-mass planet around a 0.1 solar mass M type star with 4 day periods).

Preliminary Schedule

The prototype multiple object RV instrument will be developed at the University of Florida in the fall 2004 and commissioned at Sloan in the spring 2005. This prototype instrument can observe 50 stars in one exposure with a 4kx4k CCD camera. It will be cloned for use at the WIYN in 2005 for a deeper sky survey for planets than Sloan, but with limited sky coverage. A pilot program for searching ~ 20,000 solar type stars for planets will be conducted at Sloan during the bright time between 2005-2008 after feasibility is approved. The full-scale instrument with 400 fibers including the visible and IR channels will be developed and commissioned during 2005-2008. The all sky survey will be started in 2008 using all of the telescope time available at Sloan after current survey is finished.

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