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AN ALL SKY EXTRASOLAR PLANET SURVEY WITH NEW GENERATION MULTIPLE OBJECT DOPPLER INSTRUMENTS AT SLOAN TELESCOPE

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RESUMEN

La Exploración de Planetas Extrasolares de Todo el Cielo (ASEPS) utilizaría el telescopio Sloan de 2.5-m de campo amplio y la nueva generación de instrumentos Doppler de objetos múltiples de alto rendimiento con el fin de emprender una exploración Doppler a gran escala en las bandas del visibles e IR cercano de hasta ∼250,000 estrellas relativamente brillantes ($V < 13$ y $J < 11$) y para planetas extrasolares entre 2008-2013. Una exploración continuada hasta ∼2020 podría explorar ∼250,000 estrellas adicionales y obtener información sobre planetas de periodo largo, posiblemente detectando muchos análogos solares. El objetivo de ASEPS es el de incrementar el número de planetas extrasolares en casi dos órdenes de magnitud (hasta ∼10,000 planetas durante 12 años utilizando todas las noches despejadas). Este incremento tan dramático en el número de planetas conocidos permitiría estudiar mejor las correlaciones entre las diversas propiedades de planetas extrasolares. Además, el gran número de descubrimientos de planetas permitirá detectar planetas raros que pudieron haber quedado fuera de búsquedas previas, así como también planetas en tránsito, y sistemas de planetas múltiples que interactúan entre sí.

ABSTRACT

The All Sky Extrasolar Planet Survey (ASEPS) would use the Sloan 2.5-m wide field telescope and new generation multiple object high throughput Doppler instruments to undertake a large-scale visible and near-IR band Doppler survey of up to ∼250,000 relatively bright stars (generally V up to < 13 for the visible and $J < 11$ for the near IR) for extrasolar planets between 2008-2013. An extended survey continuing until ∼2020 could survey an additional ∼250,000 stars and obtain information on long-period planets from the earlier detected planet sample, possibly detecting many solar analogs. ASEPS aims to increase the number of extrasolar planets by nearly two orders of magnitude (up to ∼10,000 planets in the 12-year survey using all clear nights). This dramatic increase in the number of known planets would allow astronomers to study correlations among the diverse properties of extrasolar planets much more effectively than at present. Additionally, the large number of planet discoveries will enable the detection of rare planets that may have eluded previous planet searches, as well as transiting planets, and interacting multiple planet systems. In March-June 2006, a single full-scale multi-object W.M. Keck Exoplanet Tracker (Keck ET) with 60 object capability was commissioned and a trial planet survey of ∼420 V=8-12 solar type stars has been conducted at Sloan telescope. Since the 2006 August engineering run, the instrument performance (throughput, image quality, and Doppler precision) has been substantially improved. Additional stars are being searched for planets.

Key Words: **EXTRASOLAR PLANETS — INSTRUMENTATION: INTERFEROMETERS — SURVEYS — TECHNIQUES: RADIAL VELOCITIES**

1. INTRODUCTION

Over the past twelve years, the extrasolar planet field has moved from the extreme fringes of astronomy to becoming part of the US president's vision for space exploration, largely due to the discovery of about 200 extrasolar planets at a dozen large ground-based telescopes since 1995 (Mayor & Quolez 1995). The vast majority of these planets were detected by using Doppler radial velocity instruments called

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cross-dispersed echelle spectrographs. However, this planet detection method has required large amount of time using the world's largest telescopes. Currently, about 5000 stars are being searched for planets with echelle instruments on a dozen telescopes around the world. Based on the current planet detection rate of 5-10% among solar type stars, it is likely that a few hundreds of planets may be detected over the next ten to fifteen years. However, currently known planets show much more diversity than expected, from the "hot Jupiters", to planets in very elongated orbits, to planetary systems with multiple Jupiter-mass planets, to the most recent: the super-Earth-mass planets in orbits with periods of a few days. These discoveries not only provide new challenges regarding planetary origins and evolution, but they also indicate a great diversity of extrasolar planet that can not be understood by discovering only a couple of hundred additional planets. A large-scale survey of tens of thousands of planets is the necessary tool to provide large enough samples to support statistically robust conclusions for a real understanding of planet formation and evolution.

ASEPS with multi-object Doppler instruments at the wide field Sloan telescope will make such a large-scale extrasolar planet survey possible. With the next generation multi-object Doppler instruments, it will allow the simultaneous observation of about 400 stars in each observing field. In 2006-2020, hundreds of thousands of stars with V=8-13 will be surveyed for detecting tens of thousands of planets.

2. PAST ACHIEVEMENTS WITH NEW GENERATION DOPPLER INSTRUMENTS

The ASEPS RV survey uses new generation Exoplanet Tracker (ET) Doppler instruments. The ET instrument design is based on a dispersed fixed-delay interferometer (DFDI) approach for RV measurements. The DFDI approach offers high throughput and multi-object capability. Instead of measuring the absorption line centroid shifts, as in the echelle approach, DFDI determines the radial velocity by monitoring interference fringe phase shifts. The concept of combining a fixed-delay interferometer with a moderate re solution spectrometer for broad band operations for high precision stellar Doppler measurements was proposed in 1997 by David Erskine at Lawrence Livermore National Lab. The initial lab experiments and telescope observations successfully demonstrated the DFDI concept for RV measurements [earlier this concept was called a fringing spectrometer and an Externally Dispersed Interferometer (EDI), Erskine & Ge 2000; Ge, Erskine, & Rushford 2002]; the theory for DFDI was described in Ge (2002). The first demons tration of this method for detecting a known planet, 51 Peg, was achieved in 2004 (van Eyken et al. 2004).

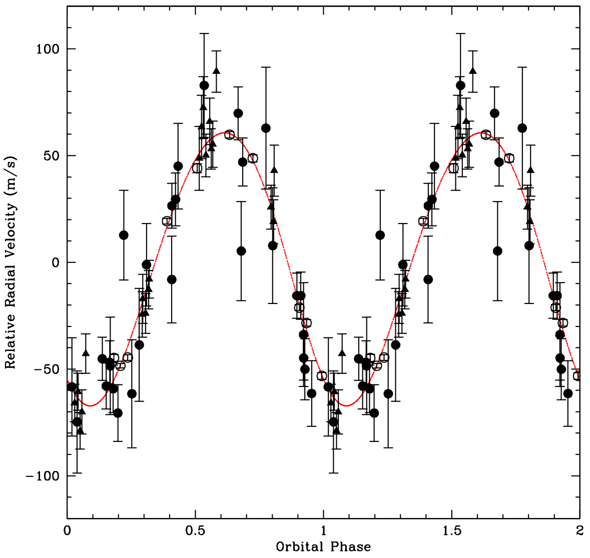

Fig. 1. Phased radial velocities for HD 102195; the KPNO Coude data are filled circles, KPNO 2.1-m data are filled triangles, and the HET data are open circles. Two orbital cycles are shown and each observation is plotted as two points (Ge et al. 2006).

To date, we have successfully developed a single-object DFDI, called ET, and produced scientific results, including the discovery of a new planet, ET-1 (HD 102195b), around a V = 8.05 G8V star, at the KPNO 0.9-meter Coude Feed/2.1-meter telescope in 2005 (Ge et al. 2006). Figure 1 presents the phased RV plot of HD102195b. This was the first time that a planet orbiting a star fainter than V=8 magnitude was discovered with the Doppler technique using a telescope smaller than 1 meter in diameter. This was possible due to the extremely high throughput of the ET instrument (despite the currently small 600 Å wavelength coverage compared to that for echelle Doppler instruments, 1200 Å to 3600 Å). The total measured detection efficiency, including the telescope, seeing, fiber, instrument and detector losses, is 18% under typical seeing conditions (1.5 arcsec) at the KPNO Coude Feed/2.1 m. This efficiency is about four times higher than that reached with the state-of-the-art echelle Doppler instrument HARPS on the ESO 3.6 meter telescope (Pepe et al. 2002).

We have measured the instrument Doppler precision and stability. With typical 10 min exposures with the 2.1-m, we reached 10 m/s Doppler precision for a V=8 star (Ge et al. 2006). Figure 2

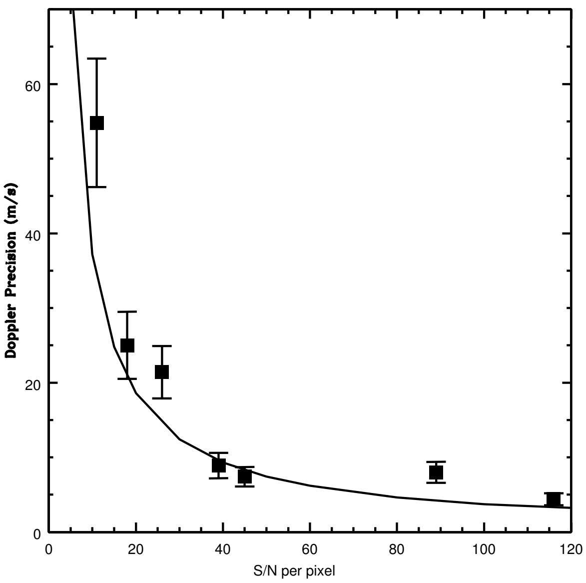

Fig. 2. Doppler precision measurements with ET. The solid line is the theoretical limit predicted by the formula in van Eyken et al. (2004). The filled square dots are the measured values from Tau Ceti with the 2.1-m telescope in Dec. 2005.

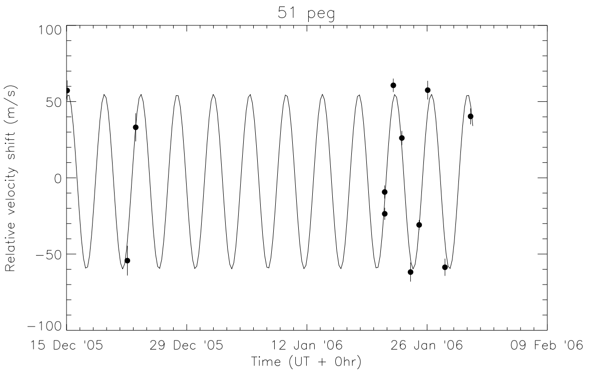

Fig. 3. RV measurements of 51 Peg with ET between Dec. 15 2005 to Jan 31 2006 at Kitt Peak. The solid line is a theoretical curve from previous publications (Naef et al. 2001).

shows measurements of the Doppler precision with ET at the KPNO 2.1-m in Dec. 2005. The best precision we reached with Tau Ceti (V = 3.5, G8V) is 4.4±0.8 m/s in 2 min exposures. The photon noise limit is 3.2 m/s. The measurements suggest that we have reached the photon noise limit in half of the cases. During the 2006 July engineering run, we have improved the instrument optical alignment and significantly reduce image aberrations, which helped to improve the Doppler precision. For instance, the photon noise limit for Tau Ceti has been improved to 2.7 m/s during the September ET run at the Kitt Peak 2.1-m.

We have measured the instrument intermediate term stability by observing 51 Peg over a few months. Figure 3 shows the measured results for the 51 Peg data during the 2.1-m runs in Dec. 2005 and January 2006. The results show that the average rms error for the individual measurement is 7.0 m/s and the rms error for the residuals after the subtraction of the planet signal is 9.7 m/s. Subtracting the photon noise error, the remaining total error is 6.7m/s, indicating that the KPNO ET is at least stable to 6.7m/s over the measurement period (∼ 45 days).

The first full-scale, new-generation, multi-object ET instrument, called W.M. Keck Exoplanet Tracker (Keck ET), has been developed in August 2005-February 2006 with the Keck Foundation support. The Keck ET inherits the single object KPNO ET design. The instrument is capable of observing 60 stars simultaneously.

In March and April 2006, the Keck ET was commissioned at the SDSS telescope. Figure 4 shows the ET fiber plugging in the Sloan fiber cartridge and also the ET instrument setup on an optical bench in a temperature stabilized room. In May and June 2006, a trial survey of 480 stars (useful data produced for 421 stars) in 8 different fields with V = 8-12 was conducted to detect new planets. A total of 10-14 RV measurements have been obtained for these survey stars. Two known extrasolar planets (HD 118203b and HD 102195b) were confirmed with the RV measurements (van Eyken et al. 2007). Several RV variables with velocity variation amplitudes less than 1000 m/s have been identified from the survey sample. Additional RV data are being taken at the Kitt Peak 2.1-m and HET telscopes to verify their nature. The 2006 August engineering improvements reduced the Doppler measurement errors by a factor of 2. The typical photon noise limited errors for stellar data are about 30 m/s for a V∼10.5 solar type star (depending on spectral type and vsini), with the best value of 6.9 m/s at V =7.6. Preliminary RMS precisions from solar data (daytime sky) are around 10 m/s over a few days, with some spectra reaching close to their photon noise limit of ∼6 m/s on the short term (∼1 hour). Additional engineering work is planned in November 2006 for further improving the instrument Doppler precision and long term stability.

In summary, the Keck ET has reached sufficient Doppler precision and throughput to execute a large-scale planet survey at the Sloan telescope. The re-

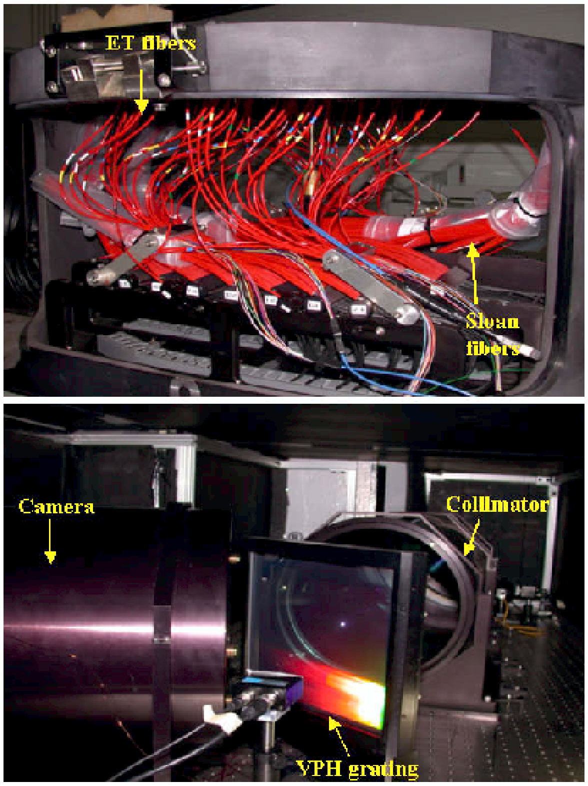

Fig. 4. (Top panel): ET fiber cartridge mounted on the SDSS telescope back. (Bottom panel): setup of the Keck ET multiple object Doppler instrument in April 2006.

maining work is to complete the optimization of the instrument performance, implement the second spectrograph arm to capture the second output of the interferometer, and to reach the design precision, throughput and long term stability for the full-scale survey.

3. ASEPS SURVEY SENSITIVITY

During the full-scale survey of ASEPS (2008-2020), we will use 7 full-scale visible multi-object ET instruments for simultaneously monitoring ∼400 solar-type stars in the visible, and 1 full-scale infrared multi-object ET for simultaneously monitoring ∼10 M dwarfs for planet detection and orbital characterization. Five of the visible multi-object ET instruments will be clones of the Keck ET. We also plan to have one multi-object visible ET instrument optimized for high precision RV measurements for stars with $V < 10.5$ to detect low mass planets by using an $R = 15{,}000$ moderate resolution cross-dispersed echelle spectrograph as a post-disperser. A total of ∼4 cross-dispersed orders will be covered per star. Recent target study shows that there are about 20 RV suitable stars with $V < 10.5$ in a typical SDSS field. This instrument will also be used for following up planet candidate stars with $V > 10.5$ to be identified by the Keck clone instruments to gain 3x Doppler precision to confirm the detection and also possibly detect additional planet companions at the SDSS telescope.

3.1. *The Visible-Wavelength Survey*

We estimate the ultimate Doppler sensitivity of the ASEPS based on the measurements by the single-object ET at the KPNO 2.1-m telescope in 2004-2005. An average Doppler precision of 8 m/s was achieved for $V = 8$ solar type stars in a 15 min exposure under good seeing conditions (consistent with the ∼ 3 m/s photon noise limited precision reached with Tau Ceti in 2 min exposure in Figure 2). Assuming this kind of performance can be reached with the Keck ET at the Sloan telescope, Table 1 lists the estimated Doppler sensitivity of the Keck ET and the high precision multi-object ET instrument. The Keck ET is capable of monitoring solar type stars with $V=11$ with a Doppler precision of ∼10 m/s and also stars as faint as $V = 13$ with a Doppler precision ∼30 m/s in an hour. With this precision we would have uncovered over 75% of the currently known exoplanets to $V = 11$, 50% to $V = 12$ and 30% to $V=13$ according to recent exoplanet statistics (Butler et al. 2006; Figure 5). With a higher dispersion (R ∼15,000 vs. R∼5,000 for the Keck ET) and a larger wavelength coverage (∼2000 Å vs. ∼900 Å with the Keck ET) than the Keck ET, the Doppler precision for each of the bright stars observed with the high precision multi-object ET instruments would be tripled (Table 1, Figure 5).

A preliminary analysis of star counts accessible to the Sloan site indicates that there are more than one million main sequence stars and also a similar number of subdwarfs and G-giant stars with $V < 13$ suitable for the planet survey. The total star counts for MS stars are estimated using previous star count surveys in the visible (Bahcall & Soneira 1980) and a dust extinction map (Schlegel et al. 1998). The star counts over the entire sky shows that there are a total of 200,000 MS stars with $V < 11$, ∼1 million MS stars with $V < 12$ and ∼5 million MS stars with $V < 13$. ∼30-40% of these stars are suitable for the survey, considering 30-40% are binaries and 30% are fast rotators with vsini > 10 km/s. According to the Yale bright star catalogue, for all of the stars with $V<6$, there are about ∼8% MS F-M stars, ∼4% F-M subgiants and ∼5% G giants, which are possible RV survey targets. If these magnitude-limited star

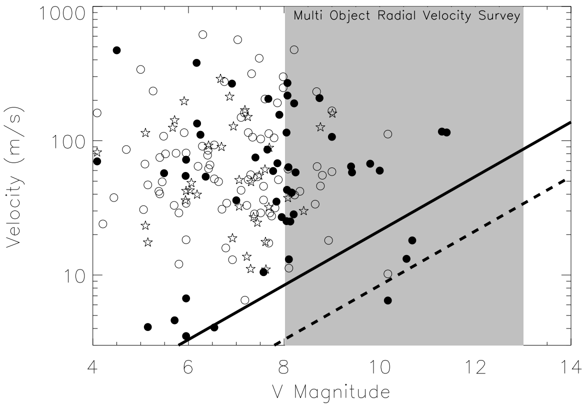

Fig. 5. Radial velocity precision expected from the SDSS multi-object ET instruments (Solid line, 3-σ velocity limit), and a multi-object high precision ET instrument with $\sim$ 20 object capability at the Sloan telescope (dahsed line). Shaded region: magnitude range of the ASEPS survey. Filled circles are known planets with P<30 days, open circles are planets with 30 days<P<3 yrs, and stars are planets with P>3yrs.

TABLE 1

DOPPLER RV UNCERTAINTIES DUE TO PHOTON NOISE OF THE KECK ET AT THE SDSS TELESCOPE, AND A PLANNED HIGH-PRECISION MULTI-OBJECT ET (ALL BASED ON A 1-HOUR INTEGRATION)

V	Sloan 2.5-m[1]	Sloan 2.5-m[2]
8	2.8 m/s	1.1 m/s
9	4.4 m/s	1.7 m/s
10	7.0 m/s	2.7 m/s
10.5	8.8 m/s	3.4 m/s
11	11.1 m/s	
12	17.5 m/s	
13	27.8 m/s	

[1] $f/1.5$ spectrograph design with R = 5,000, and a wavelength coverage of 900 Å.

[2] $f/1.3$ spectrograph design with R = 15,000, and a wavelength coverage of 2000 Å.

count statistics hold for faint stars, then we expect to have a similar number of subgiants and G giants with V<13. (However, for the G-giants, the total number may be overestimated since at V=13 G giants are several kpc from the Galactic plane so the fraction of giants should decline. A better estimate on G-giant star counts will be conducted soon.) At Sloan, the telescope can access about 60% of the entire sky. Therefore, we expect to have ~100,000 F-M MS, subgiants and G giants with V<11, ~500,000 with V<12 and ~2,000,000 with V<13 suitable for ASEPS. On an average, we will have a total of ~40 survey stars with V<11, ~150 stars with V<12, ~600 stars with V<13 in each of the Sloan fields. There are sufficient survey stars with V<13 in most of the sky regions for ASEPS to use multi-object ET instruments to obtain 400 stars simultaneously.

Since this survey star sample is unbiased with metallicity, the total percentage of stars harboring giant planets is expected to be lower than that for the RV surveys by the echelle instruments over the past 10 years. The current RV surveys have a yield of about 6.5% (Marcy et al. 2005), and this is biased toward metal rich stars (Fischer & Valenti 2005). Assuming ~2.5% (based on solar metallicity) of the ASEPS stars harbor giant planets detectable with ASEPS precision, ASEPS could detect as many as ~2,000 planets around survey stars with V <11, ~6,000 planets around stars with 11<V<12, and ~14,000 planets around stars with 12<V<13. If ASEPS were to survey a total of ~500,000 stars during its survey lifetime, then we expect to detect a total of ~10,000 giant planets.

3.2. *The Near-Infrared Survey*

We estimate the number of M dwarfs at J band by extrapolating the local number density of stars of spectral type M0 V - M8 V to J =12 (dust extinction is negligible since M dwarfs with J <12 are within ~100 pc, the constant density assumption is reasonable given that ASEPS will not reach out to distances comparable to the disk scale height for M stars). We find between 36,000 - 62,000 M dwarfs with J < 11, with the large uncertainty arising from the uncertainty of late M dwarf star counts. On average, we have about 1 M dwarf per square degree, meaning for Sloan up to ~7 suitable M dwarfs will be available in each field. One IR multiple object ET instrument with 25 object capability is sufficient for monitoring M dwarfs in each Sloan field. These numbers will be refined as the ASEPS simulations and survey optimization progresses, given the instrument sensitivities and limitations (see below) in the near-IR.

Estimating the Doppler sensitivity at J band for the IR ET is challenging since there are no IR instrument measurements for reference and because of strong telluric and OH emission lines. Our estimate is based on simulated fringing spectra of a M2V star, assuming a 5 km/s rotation velocity, a spectral resolution of R = 10,000, a wavelength cov-

TABLE 2

ESTIMATED RV SENSITIVITY WITH ASEPS NEAR THE IR MULTI-OBJECT ET INSTRUMENT (ALL BASED ON A 1-HOUR INTEGRATION)

J	Doppler precision (m/s)
6	1.9
7	3.0
8	5.0
9	7.9
10	12
11	19

erage from 1.0-1.8 μm (a cross-dispersion is required to cover such a broad wavelength region), a 3 pixel sampling, a 16% total detection efficiency (considering a lower quantum efficiency for the IR detector than the CCD), and no RV effects from telluric lines (hence the precisions are a lower limit). We compared the estimate for the visible ET using the same simulation to the measured values listed in Table 1 and the results are consistent. We find that the IR ET at the Sloan telescope can survey down to at least J = 11 (Table 2). For instance, we can achieve $\sim$19 m/s Doppler precision for a J = 11 M2V in an hour integration with the near IR multi-object ET instrument at the Sloan 2.5-m telescope. Further studies are being carried out, including atmospheric effects, optimal wavelength regions, spectral resolution etc., to estimate the Doppler errors contributed from these factors (Mahadevan et al. 2006, in preparation).

4. ASEPS SCHEDULE

The overall ASEPS program will have four major phases: a feasibility study and demonstration in 2004-2005 (phase I), a trial survey and a pilot program in 2005-2008 (phase II), a full-scale planet survey in 2008-2013 as a phase III and a phase IV for an extended survey from 2013-2020.

The phase I of the feasibility and demonstration study, which consisted of obtaining RV data using a prototype multi-object instrument, was successfully conducted in March and April 2005. The commissioning of a full scale multiple object Keck ET and a trial planet survey have been carried out during the bright time at the SDSS telescope in March to June 2006. Additional trial RV data is being taken during the bright time in September to November 2006 to characterize the instrument sensitivity (Doppler precision, short and intermediate term Doppler stability, thermal and mechanical stability) and observing constraints (brightness limit for different spectral type, observation range for each plug plate, maximum number of plug plates for each night, etc.). The goal for the trial survey is to detect a few short-period extrasolar planet candidates around solar-type stars. The pilot program will be launched shortly after the trial survey is successfully completed in November 2006 and will continue until the end of SDSS II survey in 2008. The pilot program will monitor thousands of stars for extrasolar planets with two full-scale multi-object ET instruments (120 object capability) during the bright time at the SDSS telescope.

After the SDSS II survey is completed in 2008, ASEPS proposes to use all of the available Sloan time (bright and dark time) to conduct the full-scale extrasolar planet survey through 2020. The proposed initial survey will last for 5 years (2008-2013). The extended survey (phase IV) will last for 7 years (2013-2020). The estimated total number of new planets to be detected by ASEPS is based on an assumption that the ASEPS will use all of the bright and dark time of the SDSS telescope from 2008-2020.

During ASEPS's operation, each of the selected sky areas will be visited $\sim$20 times or more during the first five years of the survey to identify planet candidates with short ($\sim$a few days) to intermediate (few years) orbital periods. Some of these planet candidates in dense star regions will be continually monitored at the Sloan telescope for more RV data points to confirm the planetary nature while new target stars in the same field will be added to the survey for detecting more planet candidates. Candidates in regions of lower stellar density will be monitored with Doppler instruments at other telescopes to acquire the complete radial velocity curves. The stars showing longer term RV variation trends as possible planet candidates in each Sloan field will be further monitored over the successive years with the Sloan telescope to cover the complete phase of the Doppler radial velocity curves of those planets.

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