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AN ALL-SKY EXTRASOLAR PLANET SURVEY WITH MULTIPLE OBJECT, DISPERSED FIXED-DELAY INTERFEROMETERS

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RESUMEN

La prospección de planetas extrasolares en todo el cielo (ASEPS) se basará en telescopios de campo amplio (inicialmente el telescopio Sloan, para luego pasar a telescopios con mayores aperturas) y una nueva generación de potentes espectrógrafos multiobjetos para dar seguimiento a millones de estrellas brillantes cercanas. ASEPS detectará decenas de miles de planetas extrasolares en las próximas dos décadas. Actualmente, ya se ha detectado un planeta (con periodo de 4.11 días y con 0.49 masas de Júpiter) alrededor de una estrella de V = 8.05 mag (Ge et al. 2006), con el telescopio de 0.9-m Coude del KPNO, con el instrumento interferométrico de retardo fijo dispersado en su version mono-objeto. En las bandas visibles, ASEPS incrementará el número de sistemas planetarios en al menos dos órdenes de magnitud, dando así una poderosa base estadística para comprender las diferentes clases de sistemas planetarios. Este estudio tiene la capacidad de detectar planetas tipo Júpiter, tanto en masa como en distancia a su estrella madre. El estudio se desarrolla en el cercano infrarrojo y puede conducir al descubrimiento de planetas tipo terrestre en las zonas habitables de estrellas poco masivas. Las observaciones recientes con el telescopio Sloan demuestran la viabilidad de la búsqueda de planetas en forma multi-objeto en paralelo al reconocimiento espectroscópico de objetos débiles SDSS. Esto sugiere que es posible combinar instrumentos Doppler con otros instrumentos astronómicos dentro de un solo paquete para incrementar la productividad científica y la eficiencia de operación, y así reducir los costos de instrumentos de los futuros grandes telescopios de campo amplio.

ABSTRACT

The All-Sky Extrasolar Planet Survey (ASEPS) is to use wide-field telescopes (initially the Sloan telescope, later with larger aperture wide-field telescopes) and new generation high-throughput multiple object Doppler instruments to monitor millions of nearby bright stars for detecting tens of thousands of extrasolar planets in the next two decades. Currently, the single-object version of the dispersed fixed-delay interferometric instrument at the KPNO Coude feed 0.9 meter telescope has already detected one planet (with period 4.11 days and mass 0.49 Jupiter masses) around a V = 8.05 mag star (Ge et al. 2006). In the visible band, ASEPS will increase the number of known planetary systems by at least two orders of magnitude, providing a powerful statistical base for understanding different kinds of planetary systems. The survey has the sensitivity to detect Jupiter-mass planets at Jupiter distances from the parent stars. The survey conducted in the near-infrared band may lead to many discoveries of terrestrial-like planets in the habitable zones around low-mass stars. Recent observations at the Sloan telescope demonstrate the feasibility of the multiple object planet survey as well as the parallel faint SDSS object spectroscopic survey. This further suggests that it is feasible to combine Doppler instruments with other astronomical instruments into one instrument package to increase the scientific productivity, and operational efficiency and to reduce the instrument cost at future large wide-field telescopes.

Key Words: **INSTRUMENTATION: INTERFEROMETERS — INSTRUMENTATION: SPECTROGRAPHS — STARS: PLANETARY SYSTEMS — TECHNIQUES: RADIAL VELOCITIES**

1. INTRODUCTION

Over the past fifteen years, the field of extrasolar planets has moved from the fringes of science to become a central pillar of current and future astronomical studies. The vast majority of the over 170 known extrasolar planets orbit main sequence stars and were found using cross-dispersed echelle spectrographs at a dozen ground-based telescopes since the detection of an extrasolar planet associated with the main sequence star 51 Peg (Mayor & Queloz 1995). There are many unexpected results concerning extrasolar planets, ranging from their extreme diversity (e.g., "hot Jupiters", planets in very elongated orbits, multiple-Jupiter-mass planetary systems) to the recently discovered super-Earth-mass planets around solar-type stars in few-day orbits.

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For a review of the state of the field, see Marcy et al. (2005). These discoveries not only provide new challenges for the fields of planetary origins and evolution, but also indicate that a large sample of planets is required to obtain a general understanding of the nature of extrasolar planets and their formation and evolution.

Although the high-precision echelle Doppler instruments have proven quite successful at detecting extrasolar planets, the current approach is costly and time-consuming because of the large sizes and relatively low throughputs (a few percent) of the spectrographs, as well as the limitation of having a single-object capability. A sample of approximately 3,000 stars (generally the closest and brightest ones) has been monitored for planets with echelle instruments on a dozen telescopes, including most of the new generation large telescopes such as the Keck, the Very Large Telescope (VLT), Subaru, the Hobby-Eberly Telescope (HET), and Magellan. Most of the target stars have a visual magnitude brighter than 8. Based on the current planet detection rate of ∼7% among solar-type stars (Marcy et al. 2005), a few hundred planets will likely be detected over the next ten years using the echelle instruments. Given the surprising range of properties known to date (and the even larger surprises that probably await us in future discoveries), this sample will be insufficient for obtaining a comprehensive picture of planet formation and evolution and their relation to stellar properties such as mass, luminosity, spectral type, metallicity, binarity, and age. Furthermore, to monitor a large number of stars, one must move to fainter targets with $V > 8$. An instrument with high throughput and multiple object capability becomes critical to monitor a large sample of dimmer stars for planets.

A promising Doppler technique for finding extrasolar planets, and one that is quite different from the echelle approach, uses a dispersed fixed-delay interferometer (DFDI) for precision radial velocity 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 idea for using a fixed-delay interferometer for high precision Doppler measurements was first proposed by solar astrophysicists in the 1970s and 1980s to measure solar oscillations (Barker & Hollenbach 1972; Gorskii & Lebedev 1977; Beckers & Brown 1978; Kozhevatov 1983). This approach was adopted by the Global Oscillation Network Group (GONG) interferometer (Harvey et al. 1995). The GONG interferometer, with a narrow bandpass (∼1 Å), has produced very high precision Doppler measurements of the sun (sub-meter per second precision for the GONG measurements; Harvey 2002).

The concept of combining a fixed-delay interferometer with a moderate resolution 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. Earlier, this concept was called a fringing spectrometer, or an Externally Dispersed Interferometer (EDI), (Erskine & Ge 2000; Ge, Erskine, & Rushford 2002b); the theory for DFDI is described in Ge (2002a). In 2002 a prototype DFDI instrument was used at the KPNO 2.1-m to reproduce the known radial velocity curve produced by the planet orbiting the solar-type star 51 Peg (van Eyken et al. 2004), demonstrating the capability of this new approach for planet detection. A new version of the instrument, designated the Exoplanet Tracker (ET), and optimized for high throughput and relatively large wavelength coverage (∼600Å) compared to the 2002 prototype (∼300 Å), was commissioned at the KPNO 0.9-m Coude feed and 2.1-m telescopes in 2003 November. The first DFDI multi-object observations, using a modified ET, were obtained in 2005 March at the 2.5-m Sloan Digital Sky Survey (SDSS) telescope at Apache Point Observatory (APO).

Below we summarize recent ET results and the status of ASEPS.

2. RECENT RESULTS USING DFDI METHOD

2.1. *Single-object ET results*

The KPNO ET has been used for a planet survey of about 200 solar-type stars with high metallicity ([Fe/H]>0.0) and V = 8-9 using the KPNO 0.9m Coude feed/2.1 m from 2004 December to 2006 February. With typical 10 minute exposures with the 2.1-m, we reached ~ 15 m s^{-1} Doppler precision for a $V \sim 8.2$ star. So far, we have discovered a new planet around HD 102195 (V = 8.05, G8V), called ET-1 (HD 102195b).

Figure 1 presents the phased radial velocity (RV) plot of HD102195 (Ge et al. 2006). The data also include the confirmation data taken the High Resolution Spectrograph at the Hobby-Eberly 9-m telescope in 2005 November − 2006 January. Our best-fit solution has a planet orbital period of P = 4.115±0.001 days, and a semi-amplitude velocity of K = 63.2±2.0 m s^{-1}. The present observations place

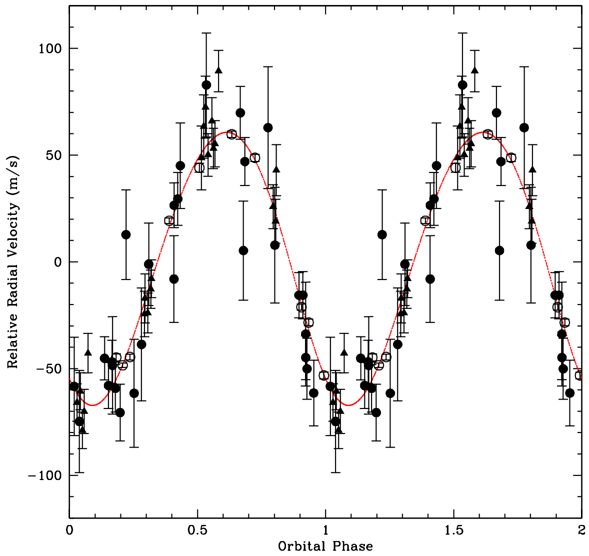

Fig. 1. Phased radial velocities for HD 102195. The KPNO Coude data are filled circles; KPNO 2.1-m data are filled triangles; and the HET data are open circles. Two orbital cycles are shown and each observation is plotted as two points (Ge et al. 2006).

upper limits on the allowed eccentricities, $e < 0.096$. Details are reported in Ge et al. (2006).

This is the first time a planet orbiting a star fainter than V=8 magnitude has been discovered with a Doppler instrument on an astronomical telescope with a diameter under one meter. This discovery became possible due to the extremely high throughput of the ET instrument despite the currently small 600 Åwavelength coverage compared to that for echelle Doppler instruments (1200 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 also measured the instrument Doppler precision and stability. Figure 2 shows systematic measurements of the Doppler precision with ET at the KPNO 2.1-m in 2005 December. The best precision we reached with Tau Ceti (V = 3.5, G8V) is 4.4±0.8 m s^{-1} in 2 min exposures. The photon noise limit is 3.2 m s^{-1}. The measurements suggest that we have reached the photon noise limit in half of the measurements.

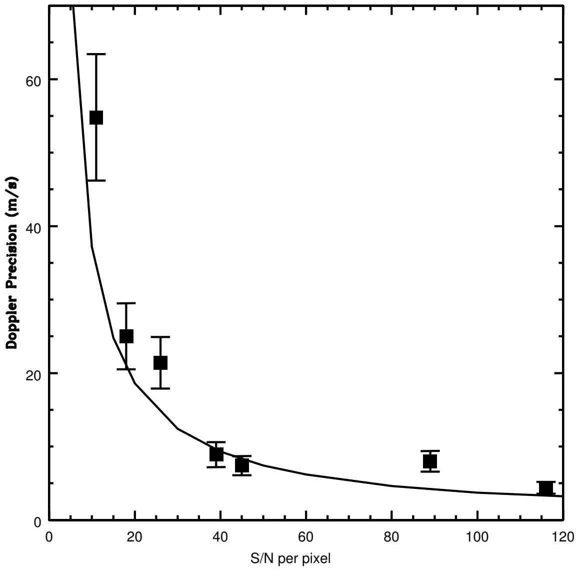

Fig. 2. Doppler precision measurements with ET. The solid line is the theoretical limit predicted by the formula in van Eyken et al. 2004. The filled squares are the measured values from Tau Ceti with the 2.1-m telescope in 2005 December.

We also began an experiment to link RV data from different observation runs to measure the instrument long-term stability. Figure 3 shows the first try for the 51 Peg data between a Coude feed run in 2005 November and a 2.1-m run in 2005 December. The results show that the average rms error for the individual measurement is 7.0 m s^{-1} and the rms error for the residuals after the subtraction of the planet signal is 12.9 m s^{-1}, indicating that a systematic error is dominant for a longer term RV measurement. Further improvements in the instrument calibration and data analysis codes are being made to reduce the systematic error and hence to allow high-precision RV measurements for a future long-term survey.

2.2. *APO Multiple Object ET Feasibility Study Results*

In 2005 March and April we demonstrated the feasibility of using the Sloan Digital Sky Survey (SDSS) telescope for multi-object Doppler measurements, and also produced scientific data from parallel observations with the SDSS faint-object spectrographs.

A prototype multiple object ET instrument was used for the SDSS feasibility study. Figure 4 shows the instrument setup at the SDSS 2.5-m telescope.

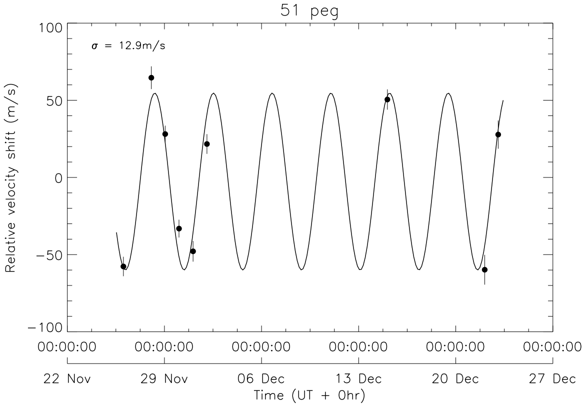

Fig. 3. RV measurements of 51 Peg with ET between 2005 November 23 to 2005 December 23 at Kitt Peak. The solid line is a theoretical curve from previous publications (Marcy et al. 1997).

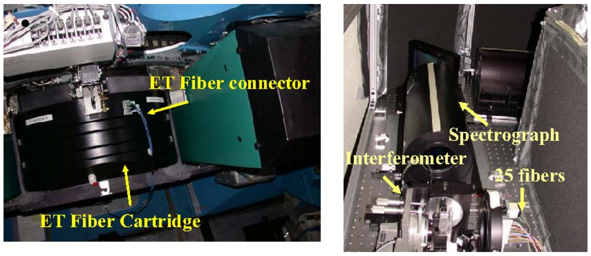

Fig. 4. (left): ET fiber cartridge mounted on the SDSS telescope back. (right): Multiple object fibers, interferometer, and spectrograph setup of the Sloan prototype ET multiple object Doppler instrument in 2005 April.

It produced 20 stellar fringe spectra simultaneously for high precision RV measurements (see Ge et al. 2005). The best Doppler precision of 10 m s^{-1} was achieved with an RV stable star, 36 UMa (V = 4.8). We were able to recover part of the Doppler curve for a planet-bearing star, 55 CnC (V = 5.95), with a Doppler precision of 11 m s^{-1}. The instrument was stable to 16 m s^{-1} over the six nights (April 20-25) measured by the 36 UMa data. Figure 5 shows the RV measurements of 36 UMa, 55 CnC, and a V=10.4 survey star. All of the measurements were conducted during the instrument first light when the thermal and mechanical conditions were not stable and the instrument had not yet reached its optimal performance.

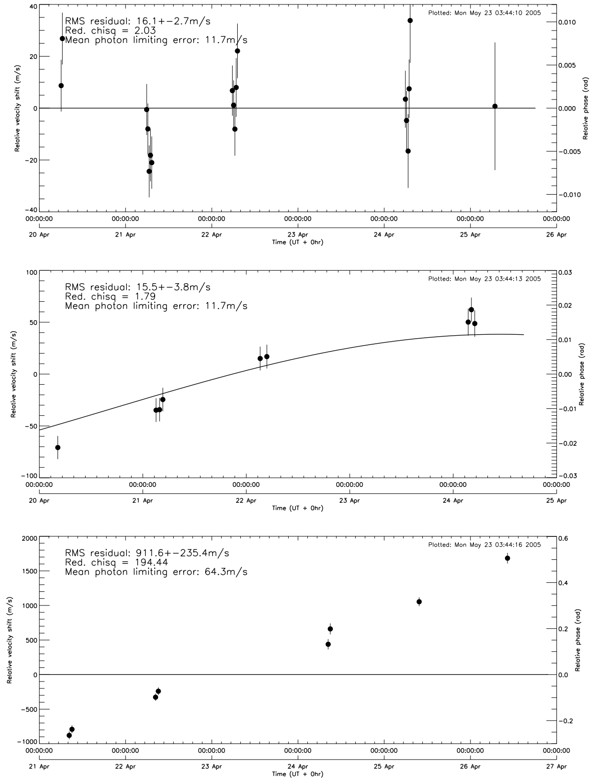

Fig. 5. RV results from three representative stars: 36 UMa (top, a RV stable star), 55 CnC (mid, a planet bearing star), and a survey star (V=10.4).

We also conducted parallel (piggy-back) spectroscopic observations of 640 *Kepler* field stars with V = 12-14 using the SDSS spectrographs during the April run while we were monitoring bright *Kepler* field stars (V = 8-11) for Doppler observations with the SDSS ET instrument. Except for the additional fiber-plugging work during the day-time, the parallel program had no operational impact on the planet survey observations.

3. AN ALL-SKY EXTRASOLAR PLANET SURVEY AND ITS STATUS

The All-Sky Extrasolar Planet Survey (ASEPS) project proposes to use the Sloan 2.5-m wide-field telescope to undertake a large-scale visible and near-IR band Doppler survey of hundreds of thousands of relatively bright stars (generally V < 13 for the visible and J < 11 for the near-IR) for extrasolar planets during 2008–2020. Following the spirit of the original SDSS goal of increasing the number of known quasar and galaxy redshifts by over one order of magnitude, ASEPS promises to increase the number of extrasolar planets by nearly two orders of magnitude. ASEPS will be the next-generation Sloan Survey.

ASEPS will detect more than 10,000 planets and these will include a wide variety of planets. The

ASEPS visible-wavelength survey has the sensitivity to detect giant planets at Jupiter-like distances (5 AU) from parent stars with V < 11. The near-infrared survey will focus on infrared-bright M stars and may lead to discoveries of super-Earth-mass planets (∼10 Earth masses) in the habitable zones (temperatures consistent with liquid water) around low-mass stars (∼0.3 solar mass). The discovery of many more planets than currently known is critical to fully understand planet formation, planet migration and evolution, the range of physical characteristics of extrasolar planets, and the relationship between planet formation and host star properties and environments. By increasing the planet sample from a few hundred to ten thousand and extending the host star mass range to 0.08–5 solar masses, the ASEPS will fuel the next generation of extrasolar planet science. In addition, ASEPS will also provide complementary work for future space planetary mission programs such as *Kepler*, Space Interferometry Mission (SIM) and Terrestrial Planet Finder (TPF).

Schedule: The overall ASEPS program will have three major phases: a feasibility study and demonstration in 2004–2005, a trial survey and a pilot program in 2005–2008, and the full-scale planet survey in 2008–2020. The feasibility and demonstration study, which consisted of obtaining RV data using a prototype multi-object instrument, was successfully conducted in 2005 March and April. The ASEPS team is now engaged in preparing for the trial survey: designing and developing a highly efficient full-scale instrument, called the W.M. Keck Exoplanet Tracker or the Keck ET (with 60-object capability) and conducting simulations to develop observing strategy. The trial survey, which will run in bright time from 2006 March until 2006 July, will fully characterize the instrument sensitivity and observing constraints. The trial survey will also detect a dozen or more short- and intermediate-period extrasolar planet candidates around 1000 solar-type stars. The pilot program will be launched shortly after the trial survey is successfully completed and will continue until 2008. The pilot program will monitor a total of 10,000 stars for extrasolar planets with two full-scale multi-object ET instruments (120-object capability).

After the SDSS II is completed in 2008, ASEPS proposes to use all of the available Sloan time to conduct the full-scale extrasolar planet survey through 2020. During this full survey phase, we will use eight full-scale visible multi-object ET instruments for simultaneously monitoring ∼400 solar-type stars in the visible, and one full-scale infrared multi-object ET for simultaneously monitoring 25 M dwarfs for planet detection and orbital characterization.

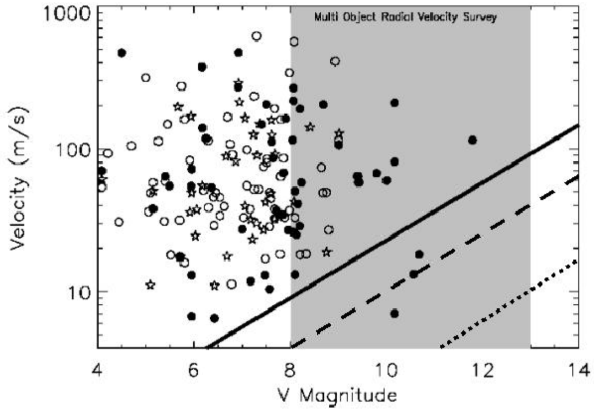

Fig. 6. Radial velocity precision expected from the SDSS multi-object ET instruments (Solid line, 3-σ velocity limit), the San Pedro Mártir 6.5-m multi-object ET instruments (dashed line) and a single-object extremely high precision ET instrument at the San Pedro Mártir 6.5-m telescope (dotted line). Shaded region: magnitude range of the ASEPS survey. Filled circles are known planets with P<10 days, open circles are planets with 10days<P<100 days, and stars are planets with 100days<P<3yrs.

Doppler Sensitivity: The ASEPS visible channel survey is capable of monitoring solar-type stars with V=8 with a Doppler precision of ∼3 m s^{-1}, V=11 with a Doppler precision of 10 m/ s and also stars as faint as V = 13 with a Doppler precision <27 m s^{-1} in an hour (Figure 6). With this precision we would have found over 75% of the currently known exoplanets to V = 11, 50% to V =12, and 30% to V=13.

The ASEPS near-IR channel survey is capable of monitoring low-mass M dwarfs with J=8 with a Doppler precision of ∼5 m s^{-1} and J=11 with a Doppler precision of ∼19 m s^{-1} in an hour.

Parallel Observations of Faint Objects: In addition to the extrasolar planet survey, we plan to extend the current Sloan Spectroscopic Survey to fainter magnitude limits than current SDSS II beyond 2008. These survey observations would be taken in parallel with ASEPS for studying extragalactic and Galactic objects and monitoring a wide range of variable sources over a long term.

Currently, the spectroscopic survey of SDSS can reach V∼19 for a point source and V∼17.8 for an extended source in an hour of integration. With a total of ∼20 visits to each of the SDSS fields with the ASEPS survey, we expect to reach ∼1.6 mag deeper

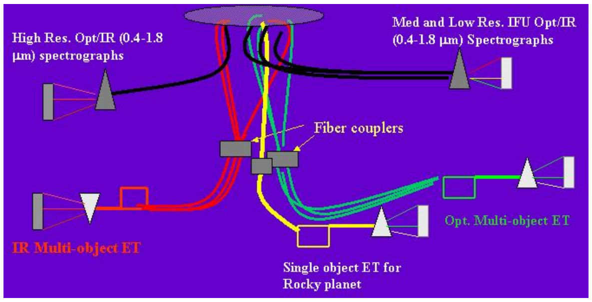

Fig. 7. A schematic layout of a Parallel Planet and Cosmology Survey instrument concept for the San Pedro Mártir 6.5-m wide-field optical/IR telescope.

than current limits with a total of 20 hours integration on faint objects, assuming the sky background is the dominant noise in the observations. We expect to reach V∼21.5 for a point source and V∼20.6 for an extended object.

4. PROPOSED PARALLEL PLANET AND COSMOLOGY SURVEY (PPCS) WITH ONE OF THE SPM 6.5-M TELESCOPES

The proposed parallel planet and cosmology survey idea at the SDSS telescope can be adapted for the future San Pedro Mártir (SPM) 6.5-m twin telescopes to take full advantage of the wide field-of-view of one of the telescope designs, and maximize its operation efficiency and productivity. Figure 7 shows a schematic layout of instruments used for the proposed PPCS. Five different kinds of astronomical instruments are included in the survey: optical and near-IR multiple object, dispersed fixed-delay interferometers for extrasolar planet detection, a single-object extremely high precision dispersed fixed-delay interferometer for detecting small mass planets; multiple object medium- and low-resolution optical/IR (0.4–1.8 μm) integral field unit spectrographs for observing faint extended and point objects; and a high resolution optical/IR (0.4–1.8 μm) spectrograph for observing point objects.

At the telescope focal plane, the SDSS fiber plug plate mechanism is adopted for plugging different fibers to different instruments. This fiber-plugging mechanism provides a maximum flexibility for observing different types of targets selected in each survey field. For an $f/5$ Cassegrain telescope design for one of the SPM twin 6.5-m telescopes, a 1.5° field-of-view corresponds to a 0.85 meter diameter focal plane. This focal plane has a factor of two more area than the SDSS focal plane. Therefore, it is possible to populate the focal plane with a total of 2000 fibers or fiber bundles (for IFU 3-D imaging spectroscopy) based on the fact that the current SDSS focal plane can hold up to ∼ 1000 fibers without technical difficulties in fiber plugging. Among the 2000 fibers for the SPM 6.5-m wide-field telescope, a total of ∼400 fibers will be reserved for planet surveys, while the remaining ∼1600 fibers or fiber bundles are used for simultaneously observing faint extragalactic objects.

At SPM, the typical seeing is 0.6 arcsec, a factor of two better than the SDSS site. Therefore, it is possible to use 1.5 arcsec fibers for the PPCS at SPM instead of the 3 arcsec fibers used at the SDSS. This should reduce the sky background by a factor of four at SPM while the SPM fibers can deliver the same throughput as SDSS fibers. This fiber operation would help to gain additional sensitivity for observing faint objects at SPM. For instance, due to the increase of the telescope collection area and also the better-seeing site, we expect to reach ∼1.8 magnitude fainter limit than the ASEPS faint-object survey for the same exposure time when the sky background is the limiting background noise. Therefore, for a 20-hour integration used for the PPCS at one of the SPM 6.5-m twin telescopes, we expect to reach V∼23.3 for a point source and V∼22.4 for an extended object with a spectral resolution of R∼2000. This spectroscopic sensitivity will allow the SPM 6.5-m to follow-up millions of faint objects identified by the LSST survey.

For the bright-object surveys, especially the extrasolar planet survey, which is limited by the photon noise of the objects, the main sensitivity gain at SPM over SDSS is due to the increased telescope aperture size. The factor of ∼ 7 times gain in the telescope photon collection power of the SPM telescope over the SDSS telescope allows us to reach two magnitude fainter stars with the same Doppler precision as the SDSS planet survey. This would allow us to potentially increase the total number of detected planets by at least a factor of two, to V = 13. Figure 6 shows the detection limits with the ET-type multiple object Doppler instruments at one of the SPM 6.5-m twin telescopes. If a single-object, extremely high precision ET instrument is used at SPM, it would be possible to detect all of the known exoplanets around stars as faint as V = 13 (see Figure 6).

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