# THE SYMBIOSIS OF PHOTOMETRY AND RADIAL-VELOCITY MEASUREMENTS

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**Abstract.** The FRESIP mission is optimized to detect the inner planets of a planetary system. According to the current paradigm of planet formation, these planets will probably be small Earth-sized objects. Ground-based radial-velocity programs now have the sensitivity to detect Jovian-mass planets in orbit around bright solar-type stars. We expect the more massive planets to form in the outer regions of a proto-stellar nebula. These two types of measurements will very nicely complement each other, as they have highest detection probability for very different types of planets. The combination of FRESIP photometry and ground-based spectra will provide independent confirmation of the existence of *planetary systems* in orbit around other stars. Such detection of both terrestrial and Jovian planets in orbit around the same star is essential to test our understanding of planet formation.

## 1. Introduction

At present, we have only one example of a planetary system to study. We have calculated elaborate models for the formation and evolution of this system. We have convinced ourselves that our solar system must be "typical" of all planetary systems, and that these models must also predict the general framework for the formation of planets around other stars. However, we have no real idea how general and robust these models will prove to be in application to planetary systems around other stars. We are in desperate need of knowledge of the nature of planetary systems around other stars. Obviously, the first step is to detect some sort of a planet around another solar-type star. But we must go beyond this important discovery of the first true extra-solar planet. We must characterize a variety of different planetary systems around a number of different stars. We need to know if "facts" we all accept are universal to all systems. Do small rocky bodies always form in the inner regions? Do larger gas-giant planets form beginning at the water condensation region? Are all systems dominated by a single large planet? Are planetary orbits always nearly coplanar? Only after we have answered these and other similar questions about several different planetary systems can we begin to understand more fully our own solar system.

All indirect methods of planet detection must attempt to measure some observable effect of the presence of the suspected planet on the light from the star. The two most common ground-based indirect techniques for planet detection are astrometry and radial-velocity measurements. These two methods measure the reflex orbital motion of the primary star around the star-planet barycenter. The photometric method of indirect planetary detection, which of course is best done from space, attempts to observe the dimming of the starlight due to transits of the planet across the stellar disk. All of these methods are complementary, in that they are most sensitive to different types of systems. Astrometry has the greatest sensitivity to nearby systems, to low-mass stars, and to planets with large semi-major axis (although the orbital periods can get to be quite large in this case). The radial-velocity signal is independent of distance to the star (except for signal/noise considerations), and is largest for planets close to the star. Both techniques are more sensitive to more massive planets. Indeed, with current techniques, astrometry and radial-velocities can only hope to detect planets of about Jupiter's mass or larger, which we do not necessarily expect to find in orbits with small semi-major axis. While the expected signal amplitude in the photometric method is also independent of the distance to the star, and is proportional to the cross-sectional area of the planet, this technique can only detect systems within a narrow range of inclination angles. However, photometry is also the *only* technique which is capable of detecting small Earth-sized planets. In the following sections, we discuss in more detail the information gained from radial-velocity planet detection work using the McDonald Observatory Planetary Search program as an example, and explore the symbiotic relationship between ground-based Doppler spectroscopy and the FRESIP program.

## 2. What do Radial Velocities Tell Us?

If we assume circular orbits (which we believe to be a reasonably good assumption for planetary systems), then the observed radial component of the velocity of the star around the system barycenter is:

$$V_\star = \frac{m_p \sin i}{M_\star + m_p}\sqrt{\frac{G(M_\star + m_p)}{a}} \tag{1}$$

The period of the orbit $P$ is given by Kepler's third law (as revised by Newton):

$$P^2 = \frac{4\pi^2 a^3}{G(M_\star + m_p)}. \tag{2}$$

If we combine these two equations, we find the observed stellar orbital velocity and the period are related by

$$V_\star = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{m_p \sin i}{(M_\star + m_p)^{2/3}} \tag{3}$$

The observable quantities are $V_\star$ and $P$. From these, and a reasonable guess at $M_\star$, we can calculate $m_p \sin i$, or a *lower limit* on $m_p$. The actual planetary mass can be estimated only when the value of the inclination angle of the system can be determined through some independent means.

The expected stellar orbital velocities for Jovian mass planets at 5-10 AU from a solar-type star are 1-50 m s$^{-1}$. These velocities are well within the precisions of current state-of-the-art ground-based radial-velocity programs, which have precisions of an individual measurement of 5-10 m s$^{-1}$. The velocities due to terrestrial planets would be around 1 cm s$^{-1}$ or less, which is undetectable with current technology.

## 3. The McDonald Observatory Planetary Search

Since September 1987, we have been obtaining high-precision radial-velocity measurements of a sample of bright F, G, and K dwarfs to search for possible planetary companions. This survey utilizes the McDonald Observatory 2.7-m telescope and its coudé spectrograph. An echelle grating used in single pass gives $R = 210,000$, and the spectrum is recorded on a TI $800 \times 800$ CCD detector. The velocity metric is supplied by a sealed, temperature stabilized gas absorption cell filled with $I_2$ vapor. Starlight is passed through the $I_2$ cell before the light enters the spectrograph. $I_2$ has a strong electronic band ($B\ ^3\Pi^+_{0u} - X\ ^1\Sigma^+_g$) in the 5000–6400Å spectral region. This $I_2$ band superimposes the rich spectrum of extremely narrow $I_2$ absorption lines on the stellar spectrum. Very precise determinations of the variations in stellar radial-velocity are made by measuring the apparent Doppler shift of the stellar lines with respect to the reference $I_2$ lines. The free parameters in the data reduction are Doppler shift and dispersion of the $I_2$ spectrum, and shift and dispersion of the "pure" stellar spectrum. Each parameter is varied to find the minimum rms deviation of the trial model spectrum from observed spectrum. This process is iterated until all parameters converge to a preset tolerance. The result is the relative radial-velocity of the star with respect to the telescope. A barycentric correction is applied using the JPL-DE303 ephemeris. Using this technique, we are able to achieve rms errors on individual measurements of bright stars of 5–10 m s$^{-1}$. The McDonald Observatory Planetary Search program is described in detail by Cochran and Hatzes (*Astrophysics and Space Science*, 1994, in press). Several examples of recent results are given there. The McDonald Observatory Planet Search will continue to use the 2.7 m coudé spectrograph at least until the completion of the Spectroscopic Survey Telescope on Mt. Fowlkes in west Texas.

In collaboration with Martin Kürster of MPI Garching, we started a companion survey of southern solar-type stars in the fall of 1992, using the 1.4 m CAT of the European Southern Observatory. This southern survey is also achieving rms errors of 5-10 m s$^{-1}$.

## 4. The Spectroscopic Survey Telescope

The Spectroscopic Survey Telescope (SST) is being built by two principal partners – the University of Texas at Austin and Pennsylvania State University, with the participation of three other associate partners – Stanford University, the University of Munich, and the University of Göttingen. The SST is a project to build a large optical telescope primarily dedicated to spectroscopy. The primary mirror is formed of 91 segments, each hexagonal in shape and 1 meter across. The complete primary mirror is 11 meters in diameter and 77 square meters in area, although not all of the primary is illuminated at any given time by focal plane assembly. The telescope is an "Arecibo type", which means that the primary mirror remains fixed during an observation, and tracking of astronomical bodies is achieved through moving the upper, secondary mirror region of the telescope. The primary is at a fixed zenith distance of 35°, and can be rotated in azimuth to access different portions of the sky. Objects can be tracked for up to one hour. The incoming light is fed by optical fibers to a variety of instruments, including a high-resolution spectrograph in a temperature controlled room under the telescope. First-light is planned for late 1996, and full science operations for late 1997.

The SST and its high-resolution spectrograph will provide an excellent opportunity for ground-based support of the FRESIP mission. We plan to begin a large, vigorous program of high-precision radial-velocity measurements using the SST. We envision expanding the present McDonald Observatory Planetary Search program to a sample of several hundred stars over the entire sky, to be monitored several times per year. In addition, the FRESIP target field is within the declination range of the SST, and a wide variety of specialized FRESIP support observations may easily be undertaken.

## 5. The Combination of Ground-Based Doppler Spectroscopy and FRESIP Results

The SST should easily be capable of obtaining high-precision ($5\,\mathrm{m\,s^{-1}}$ or better) relative radial-velocities of stars at least down to the FRESIP limit of $m_v = 12.5$. However, the FRESIP sample size of approximately 5000 solar-type stars is far too large to monitor every star at this radial-velocity precision. Instead, ground-based SST support will probably have two different components. First, a random sample of the FRESIP target stars will be routinely monitored by SST Doppler spectroscopy. This sample will be used for a number of purposes, such as determining that the FRESIP sample is "normal" in its frequency of binary stars, stellar rotation rates, chromospheric activity, etc. Second, other FRESIP stars can be observed on a *reactive* basis. In other words, FRESIP will identify potentially "interesting" targets which will be added to the SST survey list. These will be stars that have been identified as possible planetary systems on the basis of a photometric event which passes all of the tests for a possible planetary transit. SST Doppler spectroscopy of these stars will then be undertaken to search for possible radial-velocity variations. A large amount of extremely interesting material can be gained from these spectra. In any single spectrum of the star through the $I_2$ cell, the entire spectral region at $\lambda < 5000$Å is uncontaminated by $I_2$ lines. This region can be used to measure $V_r \sin i_r$ for these stars. The photometry from FRESIP will probably give an excellent measurements of the stellar rotation periods for all of the target stars. By using the best estimate of the spectral type for the star (which can be improved significantly by SST measurements of $T_e$ and $\log g$), we can estimate the stellar radius and thus the stellar rotational velocity $V_r$ for the star. By combining these results, we can get a good estimate of $\sin i_r$ for our target stars. On the assumption that $i_r \sim i_o$ (i.e. assuming that the stellar rotational axis is roughly aligned with the planetary orbital axis), we can get an independent measure of confidence in the likelihood of detecting planetary transits for a particular star.

If the star passes this preliminary "sanity check" that $i_o \sim 90°$, then a series of Doppler spectroscopy observations can be undertaken. Evidence of stellar duplicity will quickly become evident through the large amplitude of radial-velocity variations expected for normal binary systems. Lower amplitude radial-velocity variations will reveal the presence of possible Jovian-mass planets around the star. The Doppler spectroscopy would not have the sensitivity to detect the terrestrial planets which can be detected by FRESIP. However, the detection of *Jovian* planets in a system along with terrestrial planets is of extreme importance. This would indicate the existence of a *planetary system.* The scientific rationale of FRESIP is not simply to detect terrestrial planets, but to identify other planetary systems, so that our understanding of the formation of our own solar system may be tested and verified in the much larger context of several other systems. Thus, the ground-based search for gas-giant planets in a system identified by FRESIP as containing terrestrial planets would be a crucial critical test of our current paradigm of stellar and planetary-system formation.

## 6. Summary

The combination of FRESIP photometry and ground-based radial-velocity followup will provide and extremely valuable symbiosis for the detection of planetary systems. FRESIP is most sensitive to short-period inner planets, which we believe will most likely be small terrestrial-type objects. Radial-velocity measurements are most sensitive to larger Jovian-mass planets. By using radial velocities as a follow-up to candidate stars identified by FRESIP, it would be possible to identify both terrestrial and Jovian planets in orbit around another star. This would provide the long-sought major test of our current understanding of the process of planetary system formation.

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