FRESIP: A MISSION TO DETERMINE THE CHARACTER AND FREQUENCY OF EXTRA-SOLAR PLANETS AROUND SOLAR-LIKE STARS

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Abstract. FRESIP (FRequency of Earth-Sized Inner Planets) is a mission designed to detect and characterize Earth-sizes planets around solar-like stars. The sizes of the planets are determined from the decrease in light from a star that occurs during planetary transits, while the orbital period is determined from the repeatability of the transits. Measurements of these parameters can be compared to theories that predict the spacing of planets, their distribution of size with orbital distance, and the variation of these quantities with stellar type and multiplicity. Because thousands of stars must be continually monitored to detect the transits, much information on the stars can be obtained on their rotation rates and activity cycles. Observations of p-mode oscillations also provide information on their age and composition. These goals are accomplished by continuously and simultaneously monitoring 5000 solar-like stars for evidence of brightness changes caused by Earth-sized or larger planetary transits. To obtain the high precision needed to find planets as small as the Earth and Venus around solar-like stars, a wide field of view Schmidt telescope with an array of CCD detectors at its focal plane must be located outside of the Earth's atmosphere. SMM (Solar Maximum Mission) observations of the low-level variability of the Sun (~1:100,000) on the time scales of a transit (4 to 16 hours), and our laboratory measurements of the photometric precision of charge-coupled devices (1:100,000) show that the detection of planets as small as the Earth is practical. The probability for detecting transits is quite favorable for planets in inner orbits. If other planetary systems are similar to our own, then approximately 1% of those systems will show transits resulting in the discovery of 50 planetary systems in or near the habitable zone of solar-like stars.

1. Brief History

Over the centuries, much philosophical, religious, and scientific thought has been given to the possibility that other habitable or inhabited worlds exist. The intense popular interest surrounding Percival Lowell's work a century ago and the publicity surrounding the recent discoveries of planets orbiting solar-like stars as well as pulsars all testify to the continuing depth and breadth of this interest. We live at a singular moment in history in which it is has become possible for the first time to detect planets orbiting other

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star. A key step toward settling the question of the existence of other life in the Universe.

Recent discoveries have brought several surprises. Roughly Earth-mass planets have been found in orbit about two pulsars: PSR B1257+12 (Wolszczan 1994) and PSR B0329+54 (Shabanova 1995). The violent explosions that produced the pulsars were not expected to be conducive to the formation or survival of planetary systems. Hence, the discovery of planets around pulsars implies the existence of robust physical processes that readily lead to the formation of planets. However, because the supernova events that gave rise to these planets are so different from the processes that gave rise to our solar system, it is difficult to generalize from the pulsar observations to the formation of planetary systems like our own.

A second surprise is the discovery of approximately Jovian-mass planets in inner orbits about several G dwarf stars (Mayor and Queloz, 1995; Marcy and Butler, 1996). Not only do the discoveries show that our solar system is not unique in having massive planets, but they suggest that other planetary systems are likely to be significantly different than our own. Previously, only models of planetary system evolution that reproduced the characteristics of the solar system were considered useful. Now that several stars have been found with a massive planet well inside both the "ice zone" and the zone expected to account for the accretion of the rocky planets, it is clear that a substantial range of "initial conditions" and/or evolutionary histories must exist to explain the observations. It is no longer necessary to constrain all model parameters to insure that the model produces only planetary systems similar to the solar system. Preliminary results based on the presence of massive accretion disks and the coupling of planets to such disks (Lin, Bodenheimer, and Richardson 1996) suggest the possibility that planet formation and evolution in some accretion disks lead to a series of planets forming and moving inward toward the central star. Only those planets survive that have not fallen into the stellar envelope at the time the disk is cleared. These results suggest the possibility that Earth-like planets might be absent in those disks with massive inner planets.

The current theory for the formation of our solar system, the Sun, and its planets, postulates that they developed from an accretion disk formed from the collapse of a portion of a giant molecular cloud (Cameron, 1988; Shu et al., 1993). This theory also implies that planets form concurrently with most stars. Studies of stability in many-body systems indicate that most single stars, and many binary stars are expected to have planets (Lissauer, 1995). The numerical modeling of Wetherill (1991) shows that the accumulation of planetesimals after molecular cloud collapse can be expected to produce several inner planets similar to those found in the solar system. Although his results predict substantial variability in both the number and size of the planets, they often predict that two of the planets are approximately Earth-sized and that two are smaller. His results indicate that the positions of the Earth-sized planets can be anywhere from the position of Mercury's orbit to that of Mars. Therefore, a search for Earth-sized planets should cover this orbital range.

The calculations of Boss (1995) indicate that temperatures in the inner portion of the accretion disk are nearly independent of the stellar mass, but are instead controlled by the disk properties. Further, even variation of the assumed disk mass from 0.01 to 0.1 of the star's mass makes little difference in the location of the ice condensation radius and thereby the orbital distance for the formation of the giant planets. If the model is correct, then the inner planets as well as the giant outer planets should form at distances independent of the stellar and accretion disk masses. During or after their formation, angular momentum is lost to the disk and the orbital radii decrease. With the recent observations of giant inner planets around G dwarfs, this result demonstrates the need to search the region of short-period orbits.

For stars like our Sun, inner-orbit planets are likely to be the only ones to have conditions conducive to the development of life in what is referred to as the habitable zone. Figure 1 shows the habitable zone as calculated by Kasting, Whitmire, and Reynolds (1993) for main-sequence stars as a function of spectral type. The habitable zone shown here is bounded by the range of distances from a star for which liquid water would exist and by the range of stellar spectral types for which complex life had enough time to evolve (no earlier than F) and for which stellar flares and atmospheric condensation due to tidal locking do not occur (no later than K). A chapter in this volume by Kasting provides further detail. Thus, FRESIP will explore the zone with orbital periods between 0.2 to 2 years (Mercury to Mars) for stars of spectral type F0 to K5.

However, if our ideas regarding the formation of the solar system are wrong, then the measurements would show few to no inner planets around solar-like stars or show different distributions of size and position than predicted. Even a null result would be significant, as it would indicate that our understanding of planetary formation must be revised and that Earth-sized planets must be rare in our Galaxy.

2. Goals Of The FRESIP Program

While most proposed planet detection methods are sensitive to giant planets, FRESIP presents a practical way to detect small inner planets the size of the Earth or Venus, to determine the sizes of the planets and the characteristics of their orbits, and to identify those stars that should be monitored by Doppler velocity and astrometric systems to make further measurements.

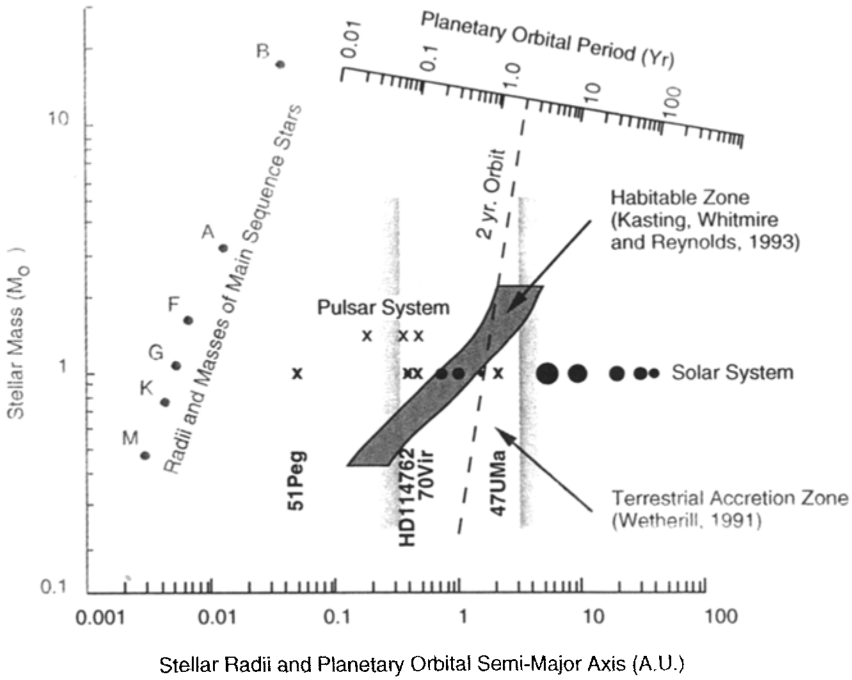


Figure 1. Relationship of stellar proerties to the habitable zone and planetary systems. Each main-sequence spectral type B, A, F, G, K, M is plotted to indicate its mass and radius on the left side of the diagram. The Terrestrial Accretion Zone and Habitable Zone are indicated. The planets in our solar system and in the B1257+12 pulsar system are shown. The scale for planetary orbital periods, based on stellar mass and orbital radius, is also indicated.

Specifically, the scientific goals and objectives of this mission are to:

- Determine the frequency of Earth-sized and larger planets in inner orbits around solar-like stars
- Determine the distributions of size and radial position of these planets
- Determine the properties of those stars found to have planetary systems
- Estimate the frequency of planets orbiting multiple-star systems
- Provide critical information on the distributions of planetary size and orbital periods for development and testing of models of planetary system formation

Rosenblatt (1971), Borucki and Summers (1984), Borucki et al. (1985), and Schneider and Chevreton (1990) have discussed several approaches for using high-precision photometric methods for detecting planets by measuring the variation of the stellar brightness and/or color that occurs when a planet transits its star. They find the photometric transit method to be particularly effective and robust. Larger planets produce a larger signal and a higher recognition rate, while smaller planets, although still detectable, have a lower recognition rate. The innermost planets have short orbital periods, and therefore show many transits for a given mission duration. Planets in larger orbits show longer transit durations but fewer transits. The geometric probability for detecting transits is quite favorable for planets in inner orbits. Once the orbital period has been determined and verified, the prediction and detection of all subsequent transits can be made. This periodic repeatability leads to a high level of confidence of discovery and should allow confirmation and follow-on studies by ground-based observatories.

Today, the FRESIP mission is practical given the acquisition of new data and the progress of technology. Variability data of adequate precision now exists for one star, our Sun, based on results from the *Solar Maximum Mission* (Willson and Hudson, 1991). Analysis of these data indicate that, even during maximum activity, the variability of main-sequence dwarf stars on the time scales of a planetary transit is a factor of eight below the amplitude change caused by the transit of an Earth-sized planet. Further, recent developments in the photometric capability of large-format Charge-Coupled Devices (CCD) have demonstrated that the precision required for the FRESIP mission is achievable (Robinson et al., 1995). By combining the new CCD technology with ultra-lightweight mirror technology, it is possible to launch an instrument above the distorting effects of Earth's atmosphere and provide continuous and simultaneous monitoring of thousands of stars with the precision necessary to detect planetary transits. A comprehensive description of the mission is given by Koch et al. (1995).

3. The Need for a Space-Based Platform

To accomplish FRESIP's goals, 5000 solar-like stars must be continuously and simultaneously monitored for evidence of the brightness changes caused by Earth-sized or larger planetary transits. The magnitude of the brightness reduction due to a transit is proportional to the ratio of the planet's area to that of the star. When observing stars the size of the Sun, the decrease in light amounts to approximately 1% for giant planets such as Jupiter and Saturn, 0.1% for planets like Uranus and Neptune, and 0.01% for planets like Earth and Venus (see Table 1). The design requirement for a system noise (instrument plus star) is to have a 1σ noise level of 1:50,000 so that a transit of an Earth-sized body ($\Delta L/L = 1/12,000$) will result in a $4\ \sigma$ detection per five-hour integration interval for the faintest star (about 12th magnitude for a 1 m aperture telescope). This level of precision includes system noise and stellar variability in the pass band between 17 mHz and 69 mHz. To obtain the precision required to detect Earth-sized planets, the photometric system must also avoid the scintillation limit incurred by ground-based observations (Young 1974). Even more limiting for ground-based observations are atmospheric transparency variations due to large air mass changes over the periods relevant to planetary transit detection. The ground-based photometric precision for events with durations of order 12 hours is less than one part in 1000 for ground-based observations even when extreme measures are taken to minimize photometric drifts (Frandsen et al., 1989; Lockwood et al., 1992). The day-night cycle and seasonal effects also make it essentially impossible to continuously monitor a single group of stars for the several years needed for reliable planet detection. Thus, a space-based mission is required.

4. Planetary Transits

4.1. ORBITAL CHARACTERISTICS

For a single star, three parameters describe the character of a planetary transit: the change in the stellar flux or brightness; the duration of the transit; and the periodic reoccurrence of the transit. The relative brightness change is used to calculate the size of the planet, while the orbital period of the planet is simply the recurrence period of the transits. The fractional brightness change, $\Delta L/L$, or transit depth is equal to the ratio of the area of the planet to that of the star. Table 1 lists these values for the solar system.

Table 1
Transit Properties for Solar System Objects

Planet	Transit Depth $\Delta L/L$ (%)	Transit Duration τ_c (hrs)	Orbital Period (yrs)	Orbital Radius R (AU)	Geometric Probability d_*/D (%)	Inclination to Ecliptic (degrees)
Mercury	0.0012	8.1	0.241	0.39	1.19	7.0
Venus	0.0080	11.0	0.615	0.72	0.64	3.4
Earth	0.0084	13.0	1.00	1.00	0.47	0.0
Mars	0.0023	16.0	1.88	1.52	0.31	1.9
Jupiter	1.01	30.	11.86	5.2	0.089	1.3
Saturn	0.68	40.	29.5	9.5	0.049	2.5
Uranus	0.116	57.	84.0	19.2	0.024	0.8
Neptune	0.096	71.	164.8	30.1	0.015	1.8

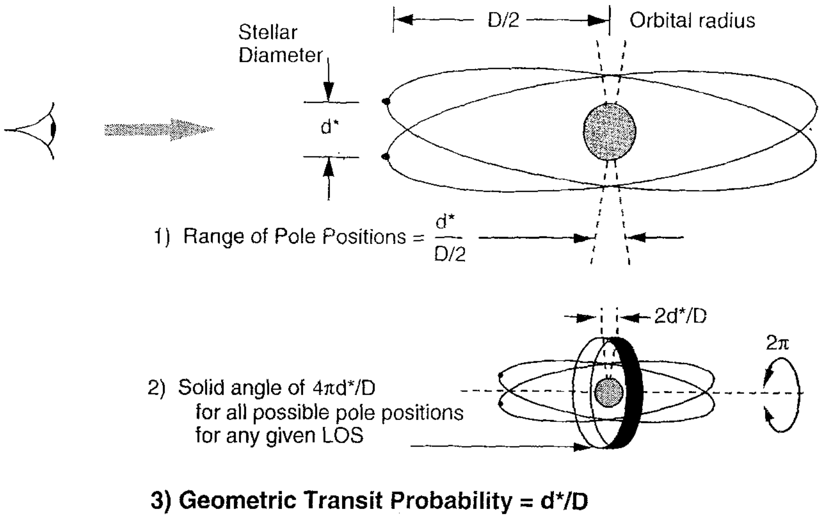


Figure 2. Geometric probability for proper orbital alignment to see a transit. The orbital plane must be within an angle $d_*/(D/2)$ of the LOS, or likewise the orbital pole must be within the same angle, for all pole positions around the LOS. The total solid angle of pole positions is $4\pi d_*/D$ sterradians, and the fraction of sky covered by this angle is d_*/D (Koch and Borucki 1994).

For transits across the center of a star, the transit duration is given by:

$$\tau_c = (13.0 \text{ hrs})\ d_* \left(\frac{R}{M_*}\right)^{1/2} , \tag{1}$$

where d_* and M_* are the stellar diameter and stellar mass in solar units, and R is the orbital radius in AU. Since d_* depends on M_* by about the 3/5 power (see Fig. 1), the transit duration is only weakly dependent on the spectral type.

4.2. GEOMETRIC PROBABILITY FOR ALIGNMENT

Transits can only be detected if the planetary orbit is near the line of sight (LOS) between the observer and the star (Figure 2). This requires that the planet's orbital pole be within an angle d_*/R, measured from the center of the star and perpendicular to the LOS, where d_* is the stellar diameter (0.0093 AU for the Sun) and $R = D/2$ is the planet's orbital radius. This is possible for all angles about the LOS, i.e., for a total of $4\pi d_*/R$ sterradians of pole positions on the celestial sphere. Thus, the geometric probability for seeing a transit for any random planetary orbit is simply d_*/D (Borucki & Summers 1984). For the Earth and Venus, this is 0.47% and 0.64% respectively (see Table 1). Because grazing transits are not easily detectable, we will ignore those with a duration less than half of a central transit. Since a chord equal to $D/2$ lies at a distance of 0.866 times the radius from the center oif the circle, the usable transits account for 86.6% of the total.

If other planetary systems are similar to our own solar system, in that they also contain two Earth-sized or larger planets in inner orbits (Wetherill 1991; Wolszczan 1994) and if the orbits are not coplanar to within $2d_*/D$, then the probabilities must be summed. Thus, approximately $0.011 \times 0.866 \approx 1\%$ of the solar-like stars with planets are expected to show transits from inner planets. Therefore, a photometric system that continuously and simultaneously monitors 5000 such stars should easily detect 50 planets if the current theory of planetary formation is correct in hypothesizing that planet formation accompanies star formation.

After a set of several transits with a sufficiently high signal-to-noise ratio (SNR) is recorded, the planet size and orbital period can be found. Then, the prediction and detection of subsequent transits for that system can be made for confirmation by independent systems. From the orbital period and the brightness change (along with stellar mass and size) one can calculate the distance from the star to the planet and the size of the planet.

Earth-sized planets in Mercury-like orbits producing four transits a year should be detected in the first year of observing. Those with Earth-like orbits will require 3–4 years of observing, and those with Mars-like orbits will require 6–8 years. For planets with orbital periods as short as those of 51 Peg b (Mayor & Queloz 1995), the detection of four transits would occur within 18 days. If, on the other hand, no small planets are discovered, the this null result would have fundamental scientific and cultural implications.

4.3. PROBABILITY OF MULTIPLE TRANSITS

Current models for planetary formation assume that the planets are formed out of a common nebula with the star, and that the orbital planes should have small relative inclinations (Hale 1994). For the solar system, these inclinations are on the order of a few degrees, except for Pluto (see Table 1). They are also small for the inner moons of Jupiter, Saturn, Uranus, and Neptune. If one were to view the solar system near either node of the intersection of the orbital planes of two planets, then clearly both planets would be observed. For very small relative inclinations of the planes, $\phi \ll 2d_*/D$, both planets would almost always be observed. For $\phi > 2d_*/D$, the probability of seeing a second planet in the system is given by (Koch & Borucki 1994),

$$P_2 = \frac{1}{\pi} \arcsin \left(\frac{\sin[2d_*/D]}{\sin \phi} \right) , \quad \text{where } \phi \geq 2d_*/D \ . \tag{2}$$

For the Venus-Earth combination, there is a 12% chance of seeing both planets. Thus, there appears to be a significant chance that multiple-planet systems will be seen. This argument tempers the previous one that the probability of detection is the sum of the individual components of each system. If the inclinations of planetary orbits in other systems were all very close to zero, the the total number of planets detected would be closer to 25. This result should lead to a further refinement of the models that describe both the frequency of planetary formation as well as the coplanarity of their orbits.

4.4. EFFECT OF MASSIVE OUTER PLANET ON TRANSIT DURATION

Calculations of of the precession of the line of nodes caused by massive outer planets show that is possible to detect their presence by monitoring the change in the duration of the transits, as the inner-planet orbital plane moves across the disk of the star. For example, assuming a solar-like star, a low-mass planet at 1 AU, a Jupiter-mass planet at 5 AU, and a 10° inclination between the two orbital planes, then for the calculated precession rate of 0.0022 degrees per year, the transit duration would change by an amount in excess of 6 minutes over an 8-year period. However, this change would occur only for the situations where the transit line was displaced from a central transit by 75% or more of the stellar radius. A more comprehensive discussion of this effect for a variety of assumptions about relative masses and orbital radii will be presented elsewhere.

5. Signal Detection in the Presence of Noise

To minimize the mission cost, it is necessary to operate at the minimum SNR and the shortest mission duration that accomplishes the goals discussed earlier. To ensure that a null result for the ensemble of observed stars is statistically meaningful, the total number of false alarms for the entire experiment must be less than one. Assuming that a uniform detection threshold is applied to each star, the required false rate can be chosen by setting the SNR threshold high enough so that the false alarm rate for each test, times the number of statistical tests performed per star, times the number of stars is less than one. Therefore, the minimum planet size that can be detected at a specific recognition rate is determined by the noise measured for each star, the number of observed transits, and the chosen value of the SNR threshold. Due to the large number of stars to be observed, the number of tests performed per star is determined in large part by the range of orbital periods and transit durations of interest, and it depends only secondarily on the power spectrum of the measurement noise. Because we want to detect planets as small as the Earth or Venus, it is important to demonstrate that the system noise can be made low enough that the SNR from four transits of an Earth-sized planet will be at least as great as the threshold value required to keep the total number of false alarms below one. In the following sections, we will show that a threshold SNR of 7σ for a set of transits is required when 5000 stars are searched for planets with orbital periods between 90 and 730 days. First, we derive the expected noise level, and then we present the results of a simulation that uses a matched filter algorithm to detect sets of transits.

The recent discovery of giant planets with orbital periods shorter than Mercury provides a motivation for searching for terrestrial planets with similar orbital periods. Although our previous discussion considered a range of planetary orbital periods, corresponding to those of the terrestrial planets in our own solar system, there is no practical barrier to expanding the search space to include planets with other periods. This expansion will not cause a dramatic increase in the required number of statistical tests, as long as the following strategy is employed: (1) Set a lower limit on the size of potential planets, so that the number of transits needed to reach the detection threshold can be calculated; (2) Conduct the search only until this time-limit is reached. By restricting attention to planets of radius comparable to or larger than the Earth, it is possible to detect such planets against an increased photon noise background coupled with shorter transits, given that four or more transits occur during the observation period. Thus, for a planet with a 15-day orbit in a grazing occultation geometry (2.2 hr duration), approximately 1.25 years of observation would be required to reach the same detection probability as for the same planet with an orbital period of one year observed for four years. This estimate includes the increased shot noise appropriate to the shorter transit duration.

The major sources of noise that are expected to compete with the transit signal are stellar variability, photon shot noise, and "instrument noise" (including detector noise and other effects such as pointing jitter). Since they are not correlated, these sources of noise can be combined as:

$$(\mathrm{SysNoise})^2 = (\mathrm{StellarVar})^2 + (\mathrm{ShotNoise})^2 + (\mathrm{InstrNoise})^2 \ . \qquad (3)$$

Table 1 showed that the expected signal level from Earth-sized planets will be approximately 8×10^{-5}. The present mission is designed to hold the total system noise to a value of 2×10^{-5}, including the effects of stellar variability. This will produce a SNR of 8σ for a a set of four transits. Note that the

SNR of a set of transits grows as the square root of the number of transits times the SNR of a signal transit, and that a four-year mission will give four transits for planets with orbital periods near one year. Thus, an eight-year mission will produce a SNR greater than 11σ. Clearly, the system noise can be kept below 2×10^{-5} only if the noise introduced by each source is below this value.

5.1. STELLAR VARIABILITY

Although many stars are variable, stellar variability will not interfere with the detection of the transits, unless the variability is at the time scale of the transits. Said another way, the noise is introduced within the band pass of the matched-filter detection algorithm. The Hertzsprung-Russell diagram has been fairly well surveyed for variability, and at this time the solar-like stars, especially older ones with low activity, are among the quietest stars known.

Much of the measured variability is found in the ultraviolet portion of the spectrum, especially in the Ca II H and K lines. Therefore, the FRESIP measurements will be confined to wavelengths longer than 400 nm. If solar-like stars have a variability similar to that of the Sun, then intrinsic brightness fluctuations will range from 10^{-3} at the rotation period of the star (due to the presence of large sunspot groups) to values of less than 10^{-5} with durations of several hours (due to turbulent motions and gravity waves in the stellar atmosphere [Frohlich 1987]). Note that the duration of a transit ranges from 4 hrs for a Mercury grazing transit to 16 hrs for a Mars central transit (see Table 1). Brightness variations with duration greater than approximately 16 hrs will not significantly affect the detectability of transits. It should also be noted that there is no reason to believe that the noise characteristic of other solar-like stars differ substantially from the Sun in the band pass of interest. Specifically, there are no other experimental data and no theories that discuss any variation of this noise with spectral type.

Figure 3 shows the measured power spectrum of the Sun, obtained with the ACRIM-1 radiometer (Woodard et al. 1982). It demonstrates that in the frequency band pertinent to planetary transits, the stellar variability noise is much less than that which occurs at frequencies characteristic of stellar rotation and the evolution of star spots. Although the effects of star spots will be observed and could show periodic brightness variations larger than those from transits from small planets, their presence will cause difficulty only for stars with both short rotation periods and extensive spotting. Studies show that rotation periods increase with stellar age (Soderblom 1983) and become quite long for stars later than spectral class F0 (Stauffer and Hartmann 1986). Spectral classes F5 through K5 have periods of weeks, sim-

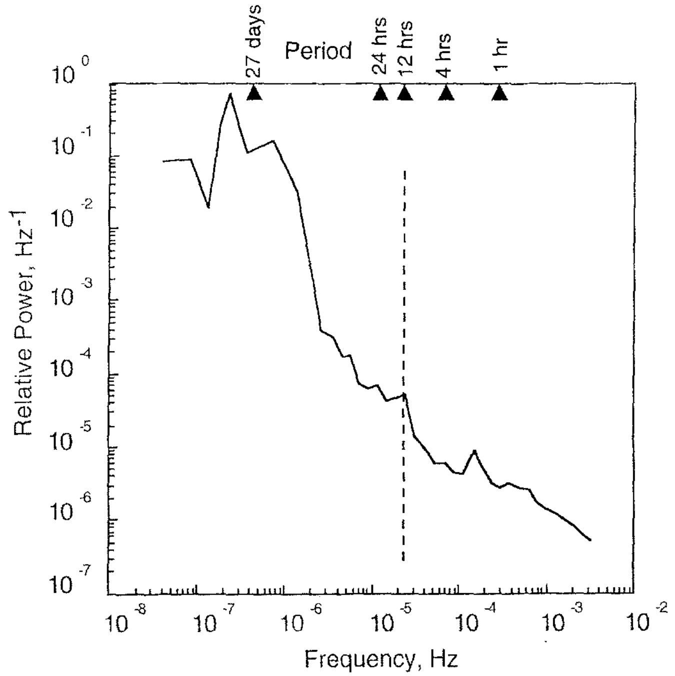


Figure 3. Power spectrum of the Sun from the ACRIM-1 (SMM) data. The intrinsic peak variability of the Sun is on the order of one part in a thousand, and the relative intensity (square root of the power) on time scales for a transit (12 hrs) is a factor of a hundred less. Thus, the variability is ~ one part in 10^5 (Woodard et al. 1982).

ilar to that of the Sun. Consequently, the presence of spots on these stars should not prevent the detection of planetary transits. Many stars earlier than F5 have rotation periods shorter than weeks. However, these stars also show much less star-spot activity, as evidenced by their lower Ca II H and K line activity (Noyes et al. 1984). Much of the variability in solar-like stars has been found to occur in the UV from ionized calcium and magnesium lines. Therefore, the short wavelength cutoff for the instrument will be at 400 nm to reduce flux variations due to Ca II lines and other UV-variable sources.

In a study being conducted at NASA-Ames, the SMM data are being examined to reduce the telemetry and instrument noise, to better estimate the noise due to the Sun's variability. Further, the contribution of the UV portion of the spectrum to the total flux measured by the ACRIM-1 radiometer is being assessed by comparison with the UV radiometric measurements made aboard the SOLSTICE spacecraft. Preliminary results from this study indicate that the solar variability in the visibel portion of the spectrum and in the band pass of interest is approximately 0.7×10^{-5}. This value implies that planets substantially smaller than the Earth should be detectable with some combination of larger apertures, longer mission durations, or shorter orbital periods.

5.2. CONTROL OF OTHER NOISE SOURCES

For the present mission design, the major source of noise is the statistical noise introduced by the finite number of photons counted. For a given integration interval, this noise an be reduced to any desired level by increasing the size of the telescope aperture and/or observing brighter stars. The first option carries a financial penalty, while the second option reduces the science yield. Tradeoff studies suggest a shot-noise error budget of 1.4 parts in 10^5, and thereby a requirement for a minimum of 5×10^9 counts per integration. The integration time available varies from 4 hrs for a grazing transit at 4 AU, to 16 hrs for a central transit at 1.5 AU. The combination of telescope aperture and efficiency, and detector bandpass and quantum efficiency, have been chosen to achieve the required sensitivity for stars with visual magnitudes of 12 and brighter (see Koch et al., 1995).

Laboratory tests of available research-grade CCDs were conducted at the expected flux levels and time durations to demonstrate the photometric precision required for FRESIP. Independent groups working at Ball Aerospace and at Lick Observatory performed tests, using relative photometry of artificial standards (ratioing the flux of an individual star to that of all other stars on the CCD). It was found that the dominant error source in the experiments was image motion, such as that caused by flexure of the mechanical system as the cryogenic coolant boiled off. By accurately centroiding star images and fitting a linear function of the relative photometry to the image position, combined with a term which fitted an observed non-linearity in CCD response as a function of brightness, Robinson et al. (1995) demonstrated that front-illuminated CCDs can routinely provide near shot-noise limited performance. A full discussion of the system noise is presented in Koch et al. (1995).

6. Simulated Transit Events

Figure 4 illustrates the difference in detectability of single and multiple transit events. Each simulation includes the three primary noise sources expected in the data: instrument noise, photon (shot) noise, and stellar variability. The simulations are generated by algebraically adding two data sets: CCD laboratory data of artificial stars with a CCD fractional error of 1.4×10^{-5}, and solar variability data from SMM with a fractional error of 1.0×10^{-5}. Pointing noise is included with the CCD data by assuming spacecraft pointing jitter (0.55 pixels or 0.16 arcsec). Because the SMM

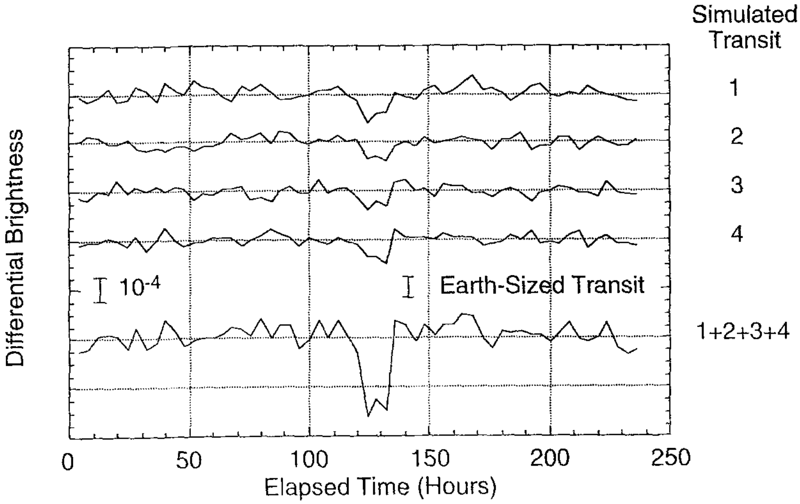


Figure 4. Detectability of transit events. Four independent simulations of an Earth-sized transit are shown. The data contain actual CCD noise and solar variability from SMM data. Gaussian shot noise and pointing equivalent noise were added. The bottom trace is a sum of four separate data sets.

data had no appreciable photon noise, Gaussian-distributed random noise was added to simulate the expected photon noise (1.4×10^{-5}). The root sum square of the errors is 2.26×10^{-5}, which is a reasonable approximation to the budgeted error of 2.0×10^{-5} and to the error measured in the simulations, which has a mean of 2.15×10^{-5}. All quantities were binned into four-hour intervals, and a 12-hour (3 data point) Venus-size transit (8.0×10^{-5}) was added to the data. A polynomial fit to the data was used with a high-pass filter. Multiple simulations show that, on average, a single transit event is a 3.5σ detection. Note that, while the data were binned into four-hour intervals, the time resolution for locating events is much higher, since the integrated brightness for target stars is taken with 15-minute centers.

The bottom plot in Figure 4 shows the result of combining or "folding" four transit data strings together. The result is a 7.5σ detection, such that 83% of planetary transits will be detected with four data strings. Note that this simulation utilizes real solar variability and real CD noise. Thus, this demonstrates that CCDs can consistently operate at the level of precision necessary for the mission, and that solar-type stars are sufficiently quiet to allow detection of transits of Earth-sized planets.

Although Figure 4 makes it easy to visualize the result of folding the entire data string for an individual star, once the phase and period of the orbit have been found, the procedure required to find the phase and period is not shown. The precedure we have chosen is to use a matched-filter algorithm, such that the time series observations for each star are first whitened and then cross-correlated with a mask whose length has a Keplerian relationship to the orbital period sought. Because the detection efficiency falls when the mismatch in the time lag is equal to the decorrelation length, a very large number of phases and periods and periods must be searched. In particular, we estimate that approximately 10^{11} statistical tests must be made when 5000 stars are searched for orbital periods between 90 and 700 days. Thus, an "event" (a set of transits) must have a SNR of at least 7σ to exceed the SNR threshold that will produce no more than 0.1 false alarms for the entire mission (or a SNR of 6.7σ if a false alarm rate of 1 event can be accepted).

Because the SNR of a set of transits increases with the square root of the number of transits, the above requirement implies that the average SNR of an individual transit must be 3.5σ for a set of four transits (i.e., a one-year orbital period for a four-year mission, or a two-year orbital period for an eight-year mission) and 1.75σ for a set of 16 transits (i.e., a 90-day orbital period for a four-year mission). The observations provide the actual noise level for each star. This noise level will be different for each star because the brightness of the target star will range from approximately 9th to 12th magnitude, and because the variability of individual stars of differing spectral class might also vary. In every case, a threshold of 7σ is applied, and only those events above the threshold will be examined further as a possible transit signal. For stars no dimmer than 12th magnitude and no noisier than the Sun, planets as small as the Earth and Venus should be detectable. For the brightest and quietest target stars and for mission durations exceeding four years, even smaller planets should be detectable. Also note that whenever the observed orbital period is short enough that more than four transits occur, it is possible to restrict further statistical tests to just the star showing the transits and to its measured orbital period. Such tests dramatically reduce the possibility of false detections.

6.1. Choice of Stellar Type

The decrease in brightness due to a transit is proportional to the ratio of the planet's area to that of the stellar disk. For a given planet size, smaller stars will provide a higher SNR than larger stars. Therefore, FRESIP will monitor main-sequence dwarf stars similar in size to the Sun, not giants or early spectral class dwarfs. We will perform spectral and luminosity classification of all stars in the field of view (FOV) to about 12th magnitude to select the target stars. Although Galactic M stars are the most abundant by total number, in a magnitude-limited sample F, G, and K stars are the most abundant, accounting for aprroximately 70% of the stars, based on SAO, HD, and AGK3 catalogs which have limiting magnitudes of $m_V \approx 9.5$.

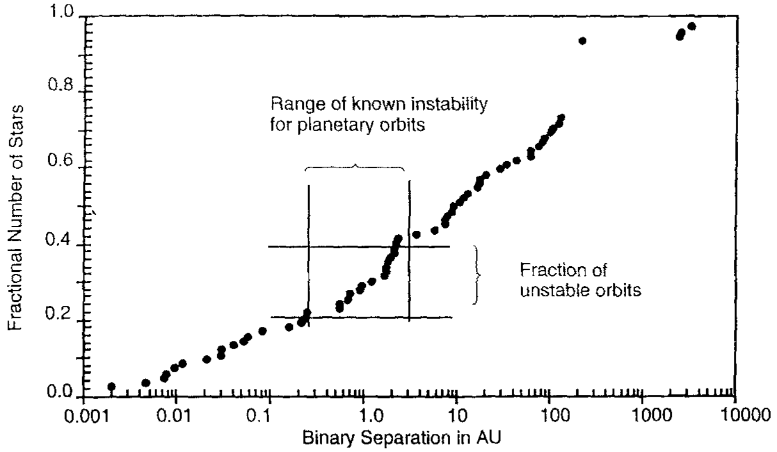


Figure 5. Distribution of binary separations (Heacox and Gathright 1994). Numerical computations have shown that planets in binary systems may have stable orbits when the planetary orbit about a close binary is at least 3.5 times greater than the binary separation, and in an open system when the planetary orbit is at least 3.5 times smaller than the binary separation. These cases account for about 77% of all solar-like binary systems.

6.2. TREATMENT OF BINARY STARS

If half the stars monitored are binaries, and if binaries do not have planetary systems, then only 25 planetary systems should be detected. However, numerical orbit integrations (Szebehely 1980; Graziani and Black 1981; Black and Pendleton 1983; Dvorak, Froeschle, and Froeschle 1989; Donnison and Mikulskis 1992) indicate the possibility of stable planetary orbits around binaries in which the planetary orbital radii are classified as either more than 3.5 times the stellar separation (close system) or less than 3.5 times the separation (open system). Based on an analysis of observed binary systems from Heacox and Gathright (1994), we can estimate the maximum number of planetary systems with orbital distances between 0.4 and 2.0 AU in binary systems (see Fig. 5).

Of the systems analyzed, close systems, in which the binary has a separation much less than Mercury's orbit, account for 17% of the cases. Open systems, where the binary has a separation at least as large as Jupiter's orbit, account for 60% of the cases. Therefore, only the remaining 23% of the systems are expected to be unsuitable for planets in the habitable zone. For open systems, planets could potentially form about both members of the binary. If a planetary transit of one of the two stars in an open binary were observed, and if both stars were of comparable brightness, then the SNR would be approximately one-half that for a similar transit occuring in a single-star system, because the stars would not be resolved by the photometer. The reduced SNR would make the transit more difficult to detect. Because the observations of the brightness distributions of companions to G dwarfs in binary stars has been tabulated by Duquennoy and Mayor (1991), it is possible to determine the fraction of G-dwarf binaries that have a secondary too dim to cause a significant reduction in the SNR of a transit. From an integration of the curves they present, we find that 85% of the binaries have secondaries that will cause less than a 20% reduction in SNR. Consequently, the fraction of solar-like binaries that could have detectable planetary systems is 17% + 0.85 × 60% = 68%. A sufficiently large number of suitable binary systems should be available: (1) to establish whether planets can be found in binary systems; and (2) to ascertain their frequency of occurrence and distribution in close and wide binaries

6.3. VIEWING CONSTRAINTS AND ORBIT SELECTION

The first viewing constraint is that the FOV must be out of the ecliptic, so that it is not blocked by the Sun on an annual basis. Low-Earth orbit is also inappropriate, since there is no part of the sky that is not blocked by the Earth as a result of orbital motion and precession of the orbital pole. From a high-Earth (several Earth radii), low-inclination orbit, portions of the sky near the equatorial poles are continuously accessible. However, these are regions well off the Galactic plane, where the star densities are relatively low. Trapped radiation also remains a problem at these altitudes. Thus, one can use a halo orbit about the Earth-Sun L2 Lagrangian point, about 0.01 AU from Earth. This orbit will permit continuous viewing of much of the sky, particularly near low Galactic latitudes where the star density is sufficiently high. Alternately, one can use a heliocentric orbit, like that proposed for the revised SIRTF (Space Infrared Telescope Facility) mission.

6.4. CHOICE OF STAR FIELD

Using the HST Guide Star Catalog as a basis for obtaining star densities, a region centered on Galactic longitude $\ell = 70°$ and latitude $b = 5°$ has been found satisfactory, in that 18,000 stars brighter than $m_V = 12$ are present in the instrument FOV. This field is at least 55° off the ecliptic, and it is not directly in the Galactic plane where giants would dominate the star counts. The fraction of these stars of the desired spectral type is estimated to be 70%, using the spectral distribution in the SAO, HD, and AGK3 catalogs. The fraction of each spectral class composed of main sequence dwarfs (luminosity class V) was estimated to be 50%, based on the Galactic model of Bahcall and Soneira (Bahcall 1986). Thus, this region should contain a sufficient number of F, G, and K stars with the required brightness.

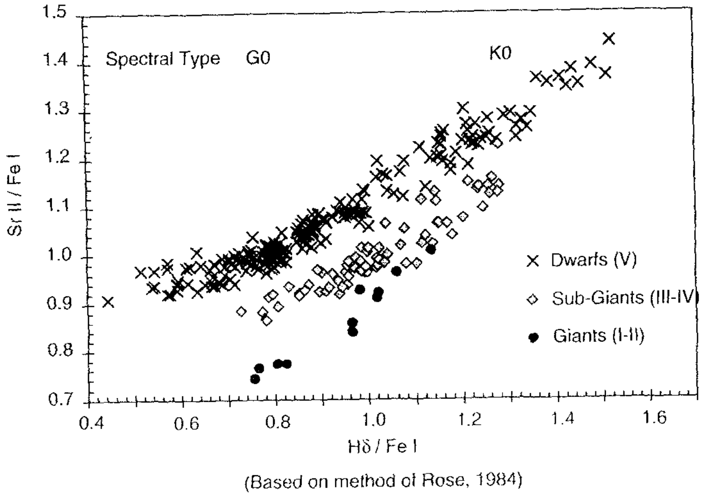
6.5. METHOD FOR SELECTING TARGET STARS

There is no existing catalog of spectral type and luminosity class containing our proposed field, down to the required magnitude limit. The HST Guide Star Catalog has a limiting magnitude of 16, but it has neither spectral or luminosity information. The AGK3 catalog, with limiting magnitide 9.5, lists only spectral type but no luminosity classification. Thus, a ground-based observing program is needed to determine the spectral type and luminosity class of each star in the FOV to about $m_V = 12$. An efficient method for performing these observations on large numbers of stars has been developed by Rose (1991). This method combines the speed and FOV of objective prism spectroscopy with the sky suppression of narrow-band photometry. A system of spectral indices is used to measure the ratio of the residual central intensity of two neighboring spectral lines. The Hδ (λ4102)/Fe I (λ4063) ratio provides the spectral-type classification for F, G, and K stars in the MK system (Morgan et al., 1943), and the Sr II (λ4077)/Fe I (λ4063) ratio provides the luminosity classification (see Fig. 6). These observations can be made using the Burrell-Schmidt telescope at Kitt Peak National Observatory and will require on the order of two weeks of telescope time.

6.6. SUPPORTING DOPPLER VELOCITY OBSERVATIONS

It will be important to maintain a ground-based observing program to determine the parameters of the eclipsing binary stars that are discovered by FRESIP. The transit signature is more complex than for the transit of a single star (Bell and Borucki 1995). However, matched-filter detection algorithms can still be used if the properties of the stars are determined from a combination of photometry and radial velocity measurements (Jenkins et al., 1995).

In addition, once a companion is found for either a singular or binary system, ground-based observations, using the Doppler method, will be needed to rule out the possibility that the transits are caused by stellar objects such as white dwarfs or substellar objects such as brown dwarfs. The precision of the Doppler velocity method often reaches 20 m s^{-1} (McMillan and Smith 1987; Latham 1992; Hatzes and Cochran 1993). Recently, Butler et al. (1996) found that they can reach a precision of 3 m s^{-1} when they use iodine absorption cells with the echelle spectrographs at either the *Keck* or



(Based on method of Rose, 1984)

Figure 6. Luminosity classification based on the measurements of three spectral lines (Rose 1991).

the *Shane* telescopes. For a precision of 3 m s^{-1}, the minimum detectable companion is given by:

$$m_p = (33\ M_{\mathrm{earth}})(R\ M_s)^{1/2}\ , \tag{4}$$

where the companion mass is given in Earth masses, the stellar mass in solar masses, and the orbital radius in AU. Thus, an Earth-mass object can readily be discriminated from a sub-stellar object and even from a Saturn- or Jupiter-mass planet.

7. Expected Results

Measurements of each star will provide the amplitude, duration, period, and epoch of each transit. The amplitude is a direct measure of the ratio of the projected area of the planet to the projected area of the star. Because both the spectral type and luminosity class of each target star will be known beforehand, from a ground-based observation program, the size of the planet can be calculated from the known size of the central star. From the epochs of a pair of transits, an estimate will be obtained of the orbital period, accurate to within one hour. Given the predicted time of transit and the identity of the star, it should be possible to use a large-aperture, ground-based telescope to verify the transits. A large aperture is required to keep the scintillation noise low enough to get a significant SNR (Young 1974). Although such telescopes do not have FOVs large enough to continuously monitor thousands of relatively bright stars ($m_V < 12$), they can measure the brightness changes at the beginning and end of a transit, when they monitor only a single target star. Because the time of transit will be known, the large telescope time is needed only when a transit is imminent.

From the mass of the star and the orbital period of the planet, the radius of the orbit can be calculated. From the orbital radius, one can determine if the planet lies within the habitable zone of the particular star and begin to make estimates of the planetary conditions (see Kasting, Whitmire, and Roberts 1993). Most significantly, FRESIP will determine whether Earth-sized planets exist in inner orbits around solar-like stars, and will measure their frequency of occurrence. Because of the statistically large sample of stellar data obtained, finding few or no planets would lead to the conclusion that Earth-sized planets are rare. Models of planetary system formation would then need to be revised, and the origin of the Earth reconsidered. On the other hand, detection of the expected number of Earth-sized inner planets would confirm currently-held theories, and would have an impact on both the scientific and public communities. The effect will be significantly enhanced if some of the detected planets are found to exist in the habitable zones for their parent star. A positive result should motivate the resources needed for more expensive programs to measure the spectra of planetary atmospheres. Furthermore, the results are necessary to provide an estimate of the range to the nearest stars with Earth-sized planets and thereby determine the size-scale of the instruments needed for such programs.

These results will also provide an estimate of the size and radial distribution of inner planets. The question as to whether only small rocky planets like the Earth are present, or whether much larger planets are also found in inner orbits, will be answered. Further observations with Doppler velocity or astrometric systems could then be used to detect any outer planets in these systems.

If our solar system is typical, with two Earth-sized planets in mildly inclined orbits, then we expect to find multiple planets in about 12% of the cases, based simply on the chance of viewing the system not too far from the line of nodes. On the other hand, if the typical relative inclinations are closer to zero and multiple planets exist, the we should almost always see multiple planets.

Depending on the nature of the result, one may be able to draw further conclusions based on the dependence of these properties on stellar type. Since about half of all stars are binary systems, we will also expect to determine the frequency of planets in binary systems. This group will subdivide into close binaries, where planets could exist in close orbit about the pair, and open binaries, where the stars are so widely separated that planets could exist around the individual members of the system. Finally, we expect to see a few transits of Jupiter-sized outer planets if most solar-like stars have such planets. Calculating the probability from d_*/D (see Table 1) and applying it to Jupiter for eight years of observing (2/3 of Jupiter's 11.86 yr orbital period) yields a probability of 6×10^{-4} of observing a transit. For 5000 stars, we would expect to see about three Jovian-type transits. Since the transit depth would be on the order of 1%, a single transit would be of very high confidence level; the signal-to-noise ratio would be 50 and the probability of a random occurrence from a Gaussian distribution would be less than 10^{-17}. Hence, only a single transit would be required for a detection. Since the inclination of the orbit would be known, Doppler velocity observations could then be used to determine the precise mass. From the photometric and Doppler velocity observations, the time of subsequent transits could be predicted. Ground-based observatories could readily observe the predicted transits of these planets, because the signal amplitude would be well above the scintillation noise. These ancillary observations would serve to confirm the detection and would determine a precise orbital period. With the mass and size information, the mean density of the planet can be calculated.

Because a very large number of stars will be observed continuously for several years, a great deal of information will be available on star spots, activity cycles, oscillations, and rotation rates. From p-mode observations, the age, mass, and composition of the stars can be obtained (Brown and Gilliland 1994). It might be possible to associate activity levels with other stellar properties and to identify the factors that control when a star is in a low activity level, such as occurred for the Sun during the Maunder Minimum. If non-solar-like stars are also included in the monitoring program, the the dependence of these properties can be studied as functions of stellar type. A more comprehensive discussion of the astrophysical application of FRESIP observations can be found in the monograph *Astrophysical Science with a Spaceborne Photometric Telescope* (Granados and Borucki 1993).

8. Summary

Results from FRESIP will provide information on the existence, sizes, and distribution of inner planets around solar-like stars. One can imagine the ramifications of the explicit knowledge of the frequency of small, possibly habitable planets in extra-solar planetary systems. For a long-duration mission and for the brightest low-noise stars, planets smaller than Earth and Venus could be detected. Thus, much of the size range of habitable planets and their distribution in and near the habitable zone will be covered. On the other hand, it would be sobering if FRESIP finds that the probability of habitable planets is so low that a null result is obtained.

In summary, FRESIP is a mission that can:

- Determine the frequency of Earth-sized and larger planets in inner orbits around solar-like stars
- Determine the distributions of size and radial position of these planets
- Determine the properties of those stars found to have planetary systems
- Estimate the frequency of planets orbiting mutiple-star systems
- Provide critical information on the distributions of planetary size and orbital periods for development and testing of models of planetary system formation

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References

Bahcall, J. N.: 1986, *Annual Review of Astronomy and Astrophysics* **24**, 577-611

Bell, J. F. and Borucki, W. J.: 1995, 'Characteristics of Transits by Earth-Sized Planets in Binary Star Systems', in *Progress in the Search for Extraterrestrial Life*, ASP Conf. Series, Vol. 74, 165-170

Borucki, W. J. and Summers, A. L.: 1984, 'The Photometric Method of Detecting Other Planetary Systems', *Icarus* **58**, 121-134

Borucki, W. J., Scargle, J. D., and Hudson, H. S.: 1985, 'Detectability of Extrasolar Planetary Transits', *Astrophysical Journal* **291**, 852-854

Boss, A. P.: 1995, 'Proximity of Jupiter-like Planets to Low-Mass Stars', *Science* **267**, 360-362

Brown, T. M. and Gilliland, R. L.: 1994, *Annual Review of Astronomy and Astrophysics* **32**, 37-82

Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., and Vogt, S. S.: 1996, 'Attaining a Doppler Precision of 3 m s^{-1}', *PASJ* **108**, 500

Cameron, A. G. W.: 1988, 'Origin of the Solar System', *Annual Review of Astronomy and Astrophysics* **26**, 441-472

Donnison, J. R. and Mikulskis, D. F.: 1992, 'Three-body Orbital Stability Criteria for Circular Orbits', *MNRAS* **254**, 21-26

Duquennoy, A. and Major, M.: 1991, 'Multiplicity among Solar-type Stars in the Solar Neighborhood', *Annual Review of Astronomy and Astrophysics* **248**, 485-524

Dvorak, R., Froeschle, C., and Froeschle, Ch.: 1989, 'Stability of Outer Planetary Orbits (P-types) in Binaries', *Astronomy and Astrophysics* **226**, 335-342

Frandsen, S., Dreyer, P., and Kjeldsen, H.: 1989, 'Stellar Photometry Stability', *Astronomy and Astrophysics* **215**, 287-304

Frohlich, C.: 1987, 'Variability of the "Solar Constant" on Timescales of Minutes to Years', *JGR* **92**, 796-800

Granados, A. F. and Borucki, W. J. (editors): 1993, 'Astrophysical Science with a Spaceborne Photometric Telescope', NASA CP-10148

Graziani, F. and Black, D. C.: 1981, 'Orbital Stability Constraints on the Nature of Planetary Systems', *Astrophysical Journal* **251**, 337-341

Hale, A.: 1984, 'Orbital Coplanarity in Solar-type Binary Systems: Implications for Planetary System Formation and Detection', *Astronomical Journal* **107**, 306-322

Hatzes, A. P. and Cochran, W. D.: 1993, 'Long-Period Radial Velocity Variations in Three K-Giants', *Astrophysical Journal* **413**, 339-348

Heacox, W. D. and Gathright, J.: 1994, 'Non-parametric Statistical Modeling of Binary Star Separation', *Astronomical Journal* **108**, 1101

Jenkins, J. M., Doyle, L. R., and Cullers, D. K.: 1995, 'A Matched-Filter Method for Ground-based Sub-Noise detection of terrestrial extrasolar planes in eclipsing binaries: Application to CM Draconis', *Icarus* **119**, 244-260

Kasting, J. F., Whitmire, D. P., and Reynolds, R. J.: 1993, *Icarus* **101**, 108

Koch, D., and Borucki, W.: 1994, in *First International Conference on Circumstellar Habitable Zones*, NASA Ames Research Center

Koch, D., Borucki, W., Cullers, K., Dunham, E., and Webster, L.: 1995, 'System design of a mission to detect Earth-sized planets in the inner orbits of solar-like stars', submitted to *JGR*

Latham, D. W.: 1992, 'Workshop Overview', in *Seeking Other Planetary Systems: The Role of Stellar Radial Velocity Measurements*, conference held at Harvard-Smithsonian Center for Astrophysics, July 12-14, 1992

Lin, D. N. C., Bodenheimer, P., and Richardson, D. C.: 1996, *Nature* **380**, 606

Lissauer, J. J.: 1995, 'Urey Prize Lecture: On the Diversity of Plausible Planetary Systems', *Icarus* **114**, 217-236

Lockwood, G. W., Skiff, B. A., and Thompson, D. T.: 1992, 'Lessons from Very Long-Term, Very High-precision photoelectric photometry', in *Stellar Photometry: Current Techniques and Future Developments*, proc. of IAU Colloq. 136, Cambridge Univ. Press, pp 99-104

Mayor, M. and Queloz, D.: 1995, 'A Jupiter-mass companion to a solar-type star', *Nature* **378**, 355-359

McMillan, R. S. and Smith, P. H.: 1987, 'Non-variability of the radial velocity of Eta Cassiopeiae A', *PASP* **99**, 849-851

Noyes, R., Hartmann, L. W., Saliunas, S. L., Duncan, D. K., and Vaughn, A. N.: 1984, 'Rotation, convection, and magnetic activity in lower main-sequence stars', *Astrophysical Journal* **279**, 763-777

Pendleton, Y. and Black, D. C.: 1983, 'Further studies on criteria for the onset of dynamical instability in general three-body systems', *Astronomical Journal* **88** 1415

Robinson, L. B., Wei, M. Z., Borucki, W. J., Dunham, E. W., Ford, C. H., and Granados, A. F.: 1995, 'Test of CCD precision limits for differential photometry', *PASP* **107**, 1094-1098

Rose, J.: 1991, 'The vertical structure of our galaxy. I. Methods of quantitative objective-prism spectroscopy', *Astronomical Journal* **101**, 937-966

Rosenblatt, F.: 1991, 'A two-color photometric for detection of extra-solar planetary systems', *Icarus* **14**, 71-93

Schneider, J. and Chevreton, M.: 1990, 'The photometric search for Earth-sized extrasolar planets by occultation in binary systems', *Astronomy and Astrophysics* **232**, 251-257

Shabanova, T. V.: 1995, 'Evidence for a planet around the pulsar PSR B0329+54', *Astrophysical Journal* **453**, 779-782

Shu, F. J., Najita, J., Galli, D., Ostriker, E., and Lizano, S.: 1993, 'The collapse of clouds and the formation and evolution of stars and disks', in *Protostars and Planets III*, eds. E. Levy and J. Lunine, Univ. of Arizona Press, pp. 3-45

Soderblom, D. R.: 1983, 'Rotational studies of late-type stars and the rotational history of the Sun', *Astrophysical Journal, Supplement Series* **53**, 1-15

Stauffer, J. R. and Hartmann, L. J.: 1986, 'Chromospheric activity, Kinematics, and Metallicity of nearby M Dwarfs', *Astrophysical Journal, Supplement Series* **61**, 531
TOPS: 1992, 'Toward Other Planetary Systems', a Report by the Solar System Exploration Division, NASA Headquarters
Szebehely, V.: 1980, 'Stability of planetary orbits in binary systems', *Celestial Mechanics* **22**, 7
Wetherill, G. W.: 1991, 'Occurrence of Earth-like bodies in planetary systems', *Science* **253**, 535-538
Willson, R. C.: 1982, 'Solar irradiance variations and solar activity', *JGR* **87**, 4319-4326
Willson, R. C. and Hudson, H.: 1991, 'The Sun's luminosity over a complete solar cycle', *Nature* **351**, 42-44
Woodard, M., Hudson, H., and Willson, R. C.: 1982, 'Variability of solar total irradiance', in *Proc. of Conference on Pulsating Stars and Cataclysmic Variables*, Boulder, CO, UCSD-SP-82-32
Wolszczan, A.: 1994, *Science* **264**, 538
Young, A. T.: 1974, 'Observational technique and data reduction', in *Methods of Experimental Physics* **12A** (ed. N. Carlton), Academic Press, New York

Panel discussion: left-to-right are Alain Léger, Anneila Sargent, Alan Stern, David Black, and Roger Angel