THE STELLAR AND PLANETARY EXPLORER (SPEX) MISSION


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ABSTRACT

The Stellar and Planetary Explorer (SPEX) is a mission designed to search for Earth-sized planets around Sun-like stars using precise photometry. The planets will be detected by searching for the decrease in brightness associated with transits of the planets in front of their parent stars. One of the secondary scientific objectives of SPEX is to do asteroseismology on a number of Sun-like stars.

SPEX is designed as a secondary payload on a commercial communications satellite and will have a design lifetime of three years. We provide an overview of the SPEX scientific objectives and design, with particular emphasis on the prospects for doing asteroseismology.

Key words: Planet Detection; Stellar Activity; Asteroseismology.

1. INTRODUCTION

The detection of terrestrial planets around other stars represents one of the most significant goals of modern astronomy and is one of the long-term goals of NASA. While extrasolar planets have been detected by ground-based Doppler-velocity techniques, all of those planets have been Jupiter-sized or larger and often in orbits close to their parent star. When the University-class Explorer (UNEX) Announcement of Opportunity (AO) was released we decided to propose a mission with this primary science objective. The proposed launch date is early in 2001.

The availability of long-term photometric monitoring of a large number of stars will allow the mission to address several other important scientific objectives. These include the detection of giant planets in reflected light, stellar activity, and, of most interest in the present context, asteroseismology of solar-like and other stars.

With a cost cap of 13M$ the UNEX missions represent the smallest of the explorer classes. This cost cap forced us to consider very low-cost ideas for the mission implementation. The proposed design has eight individual cameras each consisting of a commercial 85mm f/1.2 telephoto lens and a 20482 CCD camera. Each camera will take an exposure every 6s and sum the images over one minute for downlinking. The cameras will be mounted on a commercial telecommunications satellite and the payload will take advantage of beginning-of-life surplus power, the large downlink bandwidth offered by such a satellite, the low launch costs and the existing spacecraft structure and control.

In estimating the requirements for the proposed mission, we have made extensive use of results from two experiments on the SOHO spacecraft: the SOI-MDI experiment (Scherrer et al. 1995) and the VIRGO Sun Photometer (SPM) (Fröhlich et al. 1997). Data from these instruments provide information about the signals to be expected from Sun-like stars, as well as about potential problems of space-based CCD photometry with very high precision.

In the following we shall begin by describing the science objectives and relevant noise sources, follow with a brief description of the instrumentation and mission design and conclude with a brief analysis of the ability of the proposed mission to meet the desired scientific goals.

2. SCIENCE OBJECTIVES

As mentioned above the mission has several scientific objectives, each of which are described below. Due to the extreme photometric precision needed, the noise sources have to be considered carefully. A brief description of the significant sources is given at the end of this section.

![Diagram 1](image1.png)

**Figure 1.** The two planet-detection methods. Top shows an Earth-like planet transiting a Sun-like star and the associated light-curve. Bottom plot shows the brightness variations associated with reflected light for a close-in giant planet. Some dimensions have been exaggerated for clarity.

2.1. Planet detection

The principle behind detecting terrestrial planets by observing their transits in front of the disk of the parent star is illustrated in Figures 1 and 2. While detections clearly require a very good alignment of the orbital plane with the line of sight, observing a sufficient number of stars allow for meaningful statistical significance. Compared to other proposed methods for planet detections this method has the advantage of being reasonably efficient for the detection of small planets in small orbits. Doppler-based techniques are strongly biased in favor of giant planets in small orbits and astrometric techniques are most efficient for giant planets in large orbits around nearby stars, as is direct imaging.

The probability of the orbit inclination being such that a planet like the Earth will transit its parent star is of the order 0.5%. Given the smaller orbital radius the probability of detecting Venus is slightly higher, with the sum of the probabilities being around 1.1%. To make a null detection meaningful one needs to have an expected number of detections around 10, requiring the monitoring of the order 1000 Sun-like stars with sufficient precision. Since most fairly bright stars are not Sun-like even more stars need to be included in the field of view.

![Diagram 2](image2.png)

**Figure 2.** A series of simulated transit events generated by averaging sections of the 500nm and 865nm SPM signals used for Fig. 3, adding 370ppm of white noise and an event with a intensity drop of 0.0002 and a duration of 11 hours. At the bottom 3 events is shown. Hourly intensity averages were used. Note that 550ppm noise and drops of 100ppm are easily detectable with three transits, using appropriate processing of the time series.

The mission will also be able to detect giant planets in reflected light. The principle behind this is illustrated in the lower part of Figure 1. For a planet with the diameter and albedo of Jupiter in a 0.05AU orbit (like 51 Peg) the reflected intensity is of the order $4.8 \times 10^{-5}$ times that of the star. However, the strict periodic nature of the signal and the many orbital periods observed allows for such variations to be detected (cf. Fig. 3).

Detection of reflected light is clearly strongly biased in favor of large planets in very small orbits, similar to some of the planets detected by Doppler techniques. As it is indeed expected that several of the planets detected using this method are detectable by ground-based Doppler techniques. For a significant number of these planets transits will also be observed. Combined with Doppler measurements this will allow the determination of their orbital period, distance from the star, diameter, mass and albedo. This would clearly provide much needed information on the physical properties of such planets.

2.2. Asteroseismology

It is believed that all stars with a spectral type later than about F5 oscillate in a large number of modes, similar to those observed in the Sun, with amplitudes of a few ppm (e.g. Brown & Gilliland 1994). Currently the detections of such oscillations is, at best, tentative. Thus even the unambiguous identification...
of solar-like oscillations in another star would be of major importance. To illustrate the ability of SPEX to do so, Figure 1 shows the spectrum of solar oscillations as seen in full-disks continuum-intensity observations, as well as spectra resulting from the addition of varying amounts of white noise. The figure shows that to see modes with solar amplitudes, the noise level must be below about 150 ppm per minute of integration. Although more luminous stars are predicted to have somewhat higher amplitudes than the Sun (e.g. Houdek et al. 1995), this means that only the brightest stars observed for planet finding will have a sufficient signal-to-noise ratio to be useful.

Even so, the observation of oscillations in just a few other stars would be of major importance to asteroseismology. The determination of the so-called large and small frequency separations would allow us to calibrate stellar models substantially more accurately than currently possible. Such calibrations are essential for estimating the ages of stars and for the understanding of the evolution of the Galaxy and the Universe as a whole. The frequency resolution is also expected to be sufficiently high to allow the determination of rotational frequency splittings for some stars. This would provide measures of at least the average internal rotation rate for these stars, of substantial importance to our understanding of the evolution of rotation in solar-like stars.

In addition to the data on solar-like oscillations, SPEX would provide extensive data on the long-term behaviour of known types of variable stars, such as δ Scuti stars and slowly pulsating B stars, for which sufficiently comprehensive observations are in many cases difficult or not feasible from the ground. Asteroseismic analysis of the resulting data will provide crucial information about the evolution of a broad range of stars, including important phenomena (such as properties of convective cores) which cannot be studied in solar-like stars.

2.3. Stellar activity

As discussed below, one of the largest noise sources, for the purpose of planet detection, is the brightness variations associated with stellar activity. On the other hand, the measurement of the activity and rotation rates for a large number of stars is clearly of significant scientific interest. In particular, we shall obtain information on the level of stellar activity as a function of stellar age and spectral type, and may get some information on the presence of activity cycles. This may allow a better understanding of these processes in the Sun. Also, combining measurements of surface rotation from activity with measurements of rotational splitting may provide some information about the variation of the rotation rate with position within the stars.

2.4. Noise sources

Our ability to meet these science goals clearly depends entirely on reaching a very high photometric precision; hence it is crucially important to investigate the noise level that may be achieved with the proposed instrumentation, by analyzing the potential noise sources. For planet detection and asteroseismology the dominant noise source is expected to be
photon noise. Due to the finite CCD full-well depth and the limits on cadence, the required number of photons can only be obtained by defocusing the stellar images. For SPEX this defocusing will be in the neighborhood of 50 pixels. Defocusing also has the advantage that any remaining CCD inhomogeneities will be substantially reduced. Since the majority of photons emitted by the Sun are in the infrared long-wavelength sensitivity is desirable.

The other main noise source is the intrinsic stellar variability. While it is the subject of one of the secondary objectives, it is a significant contribution to the noise in the frequency interval used for the planet detection. This is illustrated in Figure 3. Fortunately, the time scales of the stellar activity (days to months) is long compared to that of the transits (10 hours), and the photon noise is dominant in most cases. The stellar activity is higher at shorter wavelengths, so long-wavelength sensitivity is again important.

Generally the CCD readout noise and dark current is negligible. Crowding becomes a significant problem if the stars are more defocused or fainter and is likely to be the limiting factor for detecting giant planets using transits.

3. INSTRUMENTATION AND MISSION DESIGN

Given that the number of Sun-like stars as a function of intensity follow a power law with slope $-1.5$ it may be shown that the number of observed stars is proportional to $L/f^2$, where $L$ is the focal length of the telescope and $f$ is the focal ratio. This leaves two choices for the telescopes. One is a Schmidt camera, the other a fast photographic lens. We decided to use a commercial 85 mm f/1.2 lens made by Canon. We have tested one such lens and found it to be of reasonably good quality. Another couple of lenses also look promising. Given the spacecraft constraints and the rapid development schedule a Schmidt camera, while potentially more attractive from an optical point of view, turned out not to be feasible. To get enough statistical significance (enough stars) and to allow for continuous coverage of the same regions of the sky we are proposing to use eight such cameras.

For each telescope we are proposing to use a frame transfer CCD with an imaging area of 2048 x 2048 pixels. This allows for a duty cycle close to 100% while keeping the cadence down. Each CCD will be read out every 6 seconds and summed in an onboard buffer.

Figure 5. The two nearly horizontal solid lines on this plot show the power spectra from daily images (to the left, at about $3 \times 10^{-7}$, corresponding to about 550 ppm) and from one-minute cadence images (to the right, at about $1.8 \times 10^{-8}$, corresponding to about 130 ppm). Some details of the construction of these spectra are described in the main text. Also shown (dashed) is the power spectrum from the average of the 500 nm and 662 nm channels of the SPM photometer and (dotted) the time-scale and acceptable noise level associated with a transit (cf. Fig. 3).

Some concerns have been raised about the effects of CCD stability. To investigate this we looked at calibration images from the MDI instrument in which an image of the objective is formed on the CCD. Each 8 x 8 pixel region on these images was treated as a stellar image and the relative photometric variations were determined. The resulting spectrum is shown in Figure 5. As can be seen the noise is essentially white and consistent with photon noise.

Figure 6. Proposed arrangement of the fields of view. The spacecraft rotation axis is in the center of the image. The intensity illustrates the number of cameras observing a given part of the sky. Only a circular area of each CCD has been used. The actual area used may be a combination of a disk and a rectangular area defined by the CCD. The exact placement will depend on spacecraft accommodation details. On a geostationary communications satellite the field of view would rotate every 24 hours.

As mentioned earlier we are proposing to mount the instrumentation on a commercial geostationary communications satellite. Since such a satellite rotates every 24 hours and we need to observe a field of stars continuously, we adapted a field of view around one of the celestial poles, as illustrated in Fig-
ure 6. Unfortunately, the solar panels also point in this direction; hence we are forced to distribute the cameras at the corners of the satellite to avoid having the panels transit the field of view or introduce stray light. The proposed configuration is shown in Figure 7.

Given the cheap downlink telemetry we decided not to include an onboard computer in the payload. Rather we will simply be summing the images over one minute for downlinking. While this results in a downlink rate of 5 Mbits/s this should not represent a major problem. Since we will most likely be using a TV satellite we should be able to receive the downlink signal using a small dish.

The photometry and further processing will be done on the ground. While the instrument will produce roughly 50 GB/day, experience with the MDI data processing indicates that keeping up with the data stream should not represent a significant problem.

Figure 7. Proposed placement of the cameras on the spacecraft. The fields of view (shaded) have been shown for two of the camera systems. The hatched area shows the solar panels, which must never enter the fields of view, and which rotate once every 24 h.

4. CONCLUSION

The sensitivity of the proposed instrumentation in terms of the expected number of planets detected is illustrated in Figure 8. We expect to observe about 1400 Sun-like stars with sufficient accuracy to detect a transit of an Earth-like planet. Assuming that all Sun-like stars have a planetary system similar to our system, this should yield about 6-7 Earth-like planets and a similar number of Venus-like planets. The expected number of around 13 detections would make a null result highly significant, the probability of random occurrence being of order $e^{-13} \approx 2 \times 10^{-6}$. We also expect to detect 50-100 giant planets similar to those discovered by ground-based Doppler techniques and are planning to make follow-up Doppler-based observations.

Figure 8. Number of stars with planets detectable by transits, as a function of noise to signal ratio. The lower solid line shows the number of stars taking into account the effects of crowding into account, the upper curve shows the number of stars ignoring crowding. Also shown is where the planets in the solar systems fail. For each planet (indicated by the first one or two letters) the number of stars necessary to get one (statistically significant with only one transit) detection during the mission has been indicated. For planets with orbital periods less than the mission length the points with primes indicate the S/N necessary to get a statistically significant detection with three transits. It was assumed that 15% of all stars are Sun-like (corresponding to the fraction of FGK main-sequence stars near the position of the Earth in the diagram) and that all Sun-like stars have planetary systems similar to the solar system. The fictitious planet 'R' is a Jupiter-sized planet in a 0.1 AU orbit, similar to those detected by ground-based Doppler measurements.

We also expect to detect about 50-100 giant planets in reflected light, depending on their albedo. About 10% of these should also show transits, allowing us to determine the albedos.

The number of stars for which we will be able to observe stellar activity could easily be as many as 5000-10000. This should provide a vast improvement in our understanding of stellar activity.

A search of the stars in the proposed field of view found 6 Sun-like stars for which we should obtain a photometric precision better than 100 ppm and 27 with a precision better than 150 ppm. Of the stars that may be observed with a precision of 100 ppm, 5 are F stars, with one likely to saturate the CCD, and one a K0 star. The stars observable to 150 ppm consist of two of type G0, one of type G1.5, two of type K0 and 22 F stars of various subtypes. In addition, there are a large number of A and B main-sequence stars and subgiants of various spectral types. Note that while the photometric precision required for asteroseismology is substantially greater than that required for detections of terrestrial planet transits, the design is still driven by the planet search. The asteroseismology is basically using the bright tail of the distribution of the target stars used for the planet search.
We believe that even 27 stars observed for three years will lead to a vast improvement in our understanding of stellar structure. The very long observing time compared to that proposed for dedicated asteroseismology missions means that for the stars observed we should be able to measure frequencies with a very high accuracy.

Finally, SPEX would generate long time series of images and brightness data with unprecedented accuracy, for a large magnitude-limited sample of stars. We hope that this extensive database will be useful for a variety of purposes, beyond the objectives discussed here. Indeed, as shown by recent experience with HIPPARCOS, such a rich database will be applied to many problems for which it is not primarily intended. In particular, the study of several types of variable stars should benefit substantially from such continuous monitoring.

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