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Asteroseismology with FRESIP, a Meter Class Space Telescope

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The requirements for asteroseismology and searching for occulting inner planets are similar. The FRESIP mission will be suited to making asteroseismology measurements. Recommendation: Use 30 - 60 second integrations from one or more CCDs in the FRESIP mosaic, sampled continuously for the entire mission to measure stellar non-radial oscillations with amplitudes of parts per million and frequencies of 0.1 to 10 mHz. These measurements lead to determination of stellar interior helium abundances, rotation rates, depth of convection zones and measuring stellar cycle frequency changes for a variety of stellar types, enabling major advances in stellar structure and evolutionary theories.

1.0 Asteroseismology

Asteroseismology is the study of stellar interiors through measurements of non-radial stellar oscillations. Through accurate measurements of the frequencies of the non-radial oscillations, interior properties of the star can be determined. Oscillations have frequencies in the approximate range of 0.1-10 mHz, lifetimes of days to months and longer, intensity amplitudes of parts per million.

The oscillation modes can be characterized at the stellar surface by spherical harmonics:

$$\mathrm{Re}\,(A^m_{l,n} Y^m_l(\cos(\theta), \phi) \bullet e^{i\omega_{lmn}t}) = I(t) \qquad \text{(EQ 1)}$$

Where A is the amplitude of a mode identified by degree, l, order m, and radial order n. ω_{lmn} is the cyclic oscillation frequency of the mode and Y^m_l is a spherical harmonic, θ is the co-latitude and ϕ is the longitude.

When non-radial stellar oscillations are studied with integrated light observations, only modes with order unity degree and order have measurable amplitudes, due to cancellation of bright and dark oscillating patches on the surface.

2.0 Asteroseismology Science Goals

Models of stellar structure and stellar evolution theories are based on surface measurements of stellar luminosity, temperature, surface abundance, and gravity. In the case of some nearby stars or binary stars, additional information on mass, radius and distance may be available. Stars in clusters have additional information available: they are at the same distance as the other stars in the cluster, are assumed to be the same age and initial composition.

Measurements of non-radial stellar oscillations add measurements of:

- sound speed integrated over paths that vary for each mode observed.
- convection zone depth, derived from sound speed variations as a function of depth.
- helium abundance.
- interior rotation rates.
- Interior stellar magnetic fields.

With sufficient accuracy and number of modes measured, through inverse techniques, depth resolved measurements can be made. With larger numbers of modes with shorter wavelengths, latitudinally resolved measurements can be made.

Additional information on the mode excitation and damping processes is available in the measured mode amplitudes and lifetimes. This information is not currently well understood, but holds promise for the future.

Solar oscillations mode frequencies have been observed to vary over the solar cycle. Similar frequency changes are likely to be observed for stellar cycles. For low frequency, low-l modes the change is of the order of 1 part in 10^4 per year for the sun [Libbrecht and Woodard 1990]

Stellar non-radial oscillation frequencies are sensitive to the interior helium abundance. For example, Kosovichev [1993], suggests the linearized (with respect to a stellar model) inverse equation:

$$\frac{\delta\omega_{lmn}}{\omega_{lmn}} = \int_0^R K^{lmn}_{A,Y}\delta A^* dr + J^{lmn}\delta Y + f(\omega_{lmn}) \qquad \text{(EQ 2)}$$

Where $\delta\omega_{lmn}$ is the variation in the angular frequency with respect to the model frequency ω_{lmn}. $K^{lmn}_{A,Y}$ is a kernel constructed from the mode eigenfunction, δA^* is the variation of the parameter of convective stability, A^* proportional to the radial gradient of convective stability, J^{lmn} is an integral over the reference model which represents the sensitivity of ω_{lmn} to the helium abundance, Y due to variations of plasma compressibility in zones of ionization of helium and hydrogen and $f(\omega_{lmn})$ is a term to correct for surface effects.

By inverting this expression, the unknown helium abundance, δY and a parameter related to the depth of the convection zone, δA^* can be determined.

Kosovichev [1993] shows for a 3 month observing run ($0.1\mu Hz$ frequency resolution), on a solar like star, with 25 modes observed, the helium abundance can be determined to about 1.4%, while for a 1 month observation, with only 17 modes observed the abundance is found to about 7%. Note this determination is sensitive to stellar model uncertainties and to uncertainties in the equation of state and opacities. Longer observations, leading to more accurate frequency measurements and higher sensitivity to measure more modes will lead to more precise determination of stellar interior properties.

FRESIP offers the opportunity of long time base, 6 years, continuous oscillation frequency measurements. FRESIP will permit stellar cycle measurements over a large fraction of stellar cycles.

3.0 Requirements for Asteroseismology Observations

Table 1 outlines the basic requirements for using FRESIP for asteroseismology measurements. The main differences from the occulting planet measurements include the higher observing cadence - leading to more onboard memory usage and telemetry, more stringent observation and data continuity and a more stable timebase.

TABLE 1. Basic requirements for asteroseismology measurements with FRESIP

Constraint	Value	Justification
Observation & data continuity	95%	Keep sidelobe levels low, avoid peak identification errors and frequency errors in overlapping peaks.
Observing Cadence	30-60 seconds	Observe frequencies above maximum observed solar frequencies.
Sensitivity	1 PPM averaged over weeks in the 1-200 minute period range.	Sensitivity to predicted oscillation amplitudes.
Long high cadence timebase	100+ days, repeated over years	Good frequency measurement accuracy to measure accurate stellar interior properties.
Stable timebase	~ 0.01 seconds per day	Accurate frequency measurements to avoid systematic measurement errors in the stellar properties.
Memory Required	10MB	Store 400+ stars, 24 hours, 30 second cadence.

3.1 S/N

The principle source of noise in stellar relative photometry, suitable for asteroseismological measurements is the shot noise from photon statistics. Stellar oscillation lifetimes of many cycles permit improved S/N in oscillation measurements, and random (shot) noise is averaged over the observing period. For one part per million photometry at a (minimum) signal to noise of 1, 1×10^{12} photons should be accumulated, in a maximum observing period of the order of the mode lifetimes. For 10 day mode lifetimes, this is a rate of 7×10^{7} photons per minute, or about 3×10^{6} per 2.3 second subintegration. At a signal to noise ratio of 4, this increases to about 5×10^{7} photons per 2.3 second subintegration, implying that results would improve if the stellar image could be defocussed over a larger number of pixels than the baseline 9 pixels.

3.2 Observing Cadence

Observing cadence of approximately 30 seconds to 2 minutes is required. As this is not practical with the full FRESIP field of view, either subareas from the entire field-of-view, or from a single CCD are suitable replacements.

3.3 Targets

The resolution of FRESIP is unlikely to permit globular cluster observations, but open clusters are possible targets, the presence of a bright open cluster in (or near) the field-of-view of one of the CCDs may influence the choice of CCD from the many in FRESIP to observe at high cadence.

3.4 Defocus

Ideally, for asteroseismology measurements, the defocussed stellar images should be imaged by slightly more pixels in the CCD, this improves the dynamic range for given sampling rate and reduces sensitivity to guiding errors. From above, a patch of about 50 pixels would just fill the CCD well.

3.5 Guiding

Accurate guiding is required to avoid systematic drifts from aliasing signals into the frequency range of interest. Accuracy depends on the observing time, detector non-uniformity and the amount of defocus.

3.6 Telemetry & Memory

The telemetry and onboard memory required for the asteroseismology measurements is for one intensity measurement per observing period, per star; additional stellar centroid information may aid calibration. One observing period is of the order of 30 - 60 seconds, 16.6 - 8.3 mHz Nyquist frequency (13-26 subintegration times).

Adopting the same stellar observing scheme as FRESIP uses 8 bytes per integration. With 400 stars in an asteroseismology measurement, this is a total of about 3200 bytes per 30 second integration, about 9 MBytes per day. This is about 1/2 the available on-board memory. Reducing the sampling rate to 1 minute cadence reduces the memory requirements to 4.5 MBytes per day, at the cost of reducing the observed Nyquist frequency to 8.3 mHz. Onboard compression of the data is likely to be able to reduce the memory requirements by another factor of two.

The aim is to maintain 95% or better data continuity, to achieve this, some data may be sent redundantly. If 10 MB are allocated for these high cadence observations, and the data is stored in compressed form, with a compression factor of 2, then two copies of the data for 400 stars can be saved, the data can be sent twice, over a two day period to improve the data continuity.

3.7 Calibration

The asteroseismology measurements have straightforward calibration requirements, assuming the instrument is stable for periods much longer than the longest periods to be observed.

The CCD data should be corrected for known CCD effects such as gain and dark current. Systematic effects on entire field-of-view can be calibrated out of the signal on the ground. The main source of error requiring accurate flat fielding is image drift due to tracking errors, the quality of the flat field required is dependent on the size of the tracking errors.

3.8 Ground processing

The data from the spacecraft will consist of a timeseries of intensity measurements for selected stars. The data will be temporally Fourier transformed, peaks found, identified and fit to measure frequency as a function of mode. Systematic errors can be removed from the frequency spectrum by identifying intensity correlations between stars caused by instrumental systematics and in the frequency spectrum by searching for co-incident peaks in all spectra.

3.9 Timebase accuracy

The timebase should be accurate to better than the longest integration times, for 100 day integrations, 100 nHz frequency resolution is available, the timebase should be accurate to at least 10 times this, about 10 nHz frequency in 100 days, or 1 ppm. For 1000 day integrations, 0.1 ppm, or about 0.01 seconds per day.

4.0 Advantages of FRESIP for Asteroseismology

The advantage of high orbit space based measurements for asteroseismology include:

1. No seeing.
2. No transparency variations.

3. No day night illumination cycles.
4. No day night thermal variation cycles.
5. Single site/single detector.
6. No seasonal effects: continuous measurements several years possible.

These lead to stable measurements, sensitive to long period oscillations that probe stellar cores. Ground based observations have gaps and systematic noise sources with sidelobes spaced at integer multiples of 1/day in frequency.

FRESIP is a mission with very similar requirements to those required for asteroseismology. The extra costs for the changes for an asteroseismology capability are minimal, mainly extra onboard memory and telemetry (already planned) to maintain the faster observing cadence.

Ground based observing, comparable in quality to FRESIP, requires a dedicated network of 6 telescopes, spread in longitude and latitude, probably with four meter or larger apertures. Due to large amplitude, low frequency noise sources, a ground based network will probably still not perform as well as FRESIP.

4.1 Observing Strategy

To make the best use of the large FRESIP field of view and the long duration of the mission, multiple selections of stars can be studied. A possible mixture of selections might be to start with a secondary selection for 100 days, then switch to a prime selection for 300 days, back to the secondary selection for 100 days (giving a long baseline for stellar cycle changes), back to the prime selection for 300 days, back to the secondary selection for 100 days, then a tertiary selection for 100 days, followed by briefer (50 day?) measurements of several remaining selections, finally switching back to the prime selection for the remainder of the spacecraft lifetime.

An alternate strategy is to observe selected stars from the entire FRESIP mosaic for the entire mission.

5.0 Recommendation

Use a set of selected stars from the entire field-of-view, for high cadence continuous observations for asteroseismology. These measurements will lead to precise stellar interior helium abundance measurements, leading to information on the age and composition of the universe, and to detailed measurements of stellar structure, leading to improved stellar evolutionary models.

References

A.G. Kosovichev, “Seismic Measurements of the Helium Abundance and the Depth of Stellar Convection Zones,” *Astron. Astrophys.*, submitted, 1993.

K.G. Libbrecht and M.F. Woodard, Solar Cycle Effects on Solar Oscillation Frequencies, *Nature,* Vol. 345, 779, 1990.