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*Proceedings of the First FRESIP Astrophysics Workshop
held at the SETI Institute, Mountain View, California
November 11–12, 1993*

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Astrophysical Science with a Spaceborne Photometric Telescope

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National Aeronautics and
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Ames Research Center
Moffett Field, California 94035-1000

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Preface

The FRESIP project (FRequency of Earth-Sized Inner Planets) is currently under study at NASA Ames Research Center. The goal of FRESIP is the measurement of the frequency of Earth-sized extra-solar planets in inner orbits via the photometric signature of a transit event. This will be accomplished with a spaceborne telescope/photometer capable of photometric precision of two parts in 100,000 at a magnitude of $m_v = 12.5$. The photometric instrument is a meter class (clear aperture) compound telescope with a wide field of view (~100 square degrees). The instrument will be flown in a 15,000 km altitude, ten degree inclination orbit and is designed to stare continuously at the same star-field for the duration of the six-year mission. A minimum of six years is needed to allow repeated detection of transits with orbital periods from three months to two years; a predictably periodic event is required for detection of a planet. That is, a planet is detected when a third transit can be predicted based on the observation of two previous events (duration, period, and amplitude). The current design is for a simple instrument with no moving parts that will be flown with a Delta II launch vehicle.

In order to achieve the maximum scientific value from the FRESIP mission, the FRESIP research team at Ames Research Center held an astrophysical science workshop at the SETI Institute in Mountain View, California, on November 11–12, 1993. Workshop participants were invited as experts in their field of astrophysical research. As such, the purpose of the workshop was to discuss the astrophysical science that can be achieved within the context of the FRESIP mission. Each participant made a 20 minute presentation discussing the science within their specialty that could be done with the FRESIP mission, how the measurements would address important scientific problems, and the experimental requirements. A round table discussion was conducted to create a list of recommended astrophysical research that can be done which is unique to the FRESIP platform while requiring no significant changes to the FRESIP planetary detection mission design.

The photometric data set which will be created by FRESIP is unprecedented in astronomy; participants agreed that FRESIP will provide a data set with:

- long term observations (six year baseline)
- continuous observing (one hour integrations 24 hours/day, 365 days/year)
- high precision photometry (accuate to a few parts in 10^5)
- data for several thousand point sources in the FRESIP field of view.

While the primary purpose of gathering the data set is the discovery of Earth-sized inner planets using high precision photometry, this science workshop came up with many additional scientific objectives that can be accomplished with FRESIP. These objectives fall into three broad categories.

- Solar and stellar physics: including star spots, activity cycles, oscillations, rotation rates, and flares.
- Stellar variability: including cataclysmic variables, RR Lyra stars, and δ-Scuti stars.
- Extragalactic objects: primarily quasars and other point source active galactic nuclei (AGN).

The types of research which can be conducted in these areas are summarized below, and discussed in detail in the articles which comprise these proceedings.

I. SOLAR AND STELLAR PHYSICS

The FRESIP field of view will include roughly 5000 solar-type stars (spectral class F, G, and K dwarfs) brighter than twelfth magnitude. The high precision broad band photometry and continuous time coverage will provide otherwise unattainable data on such things as white light flares on other stars, mapping of star spots, determination of rotation rates, and monitoring of stellar activity cycles. The quality statistics and long term continuous time coverage of objects will provide a high quality census of solar-like stars and thereby define the range of possible behavior that the Sun may exhibit. This information will be valuable not only to stellar astrophysicists, but also to atmospheric scientists, paleoclimatologists, and others researching the impact of a changing Sun on the Earth's biosphere.

FRESIP will also be capable of measuring p-mode oscillations associated with the interior physics of stars. Currently asteroseismologists have had limited success with stars other than the Sun through the use of world-wide observing networks that require large investments of time, money, and organizational effort for a relative small return on the investment. By modifying the data rate to obtain one minute integrations for a selected subset of several hundred target stars, FRESIP will provide asteroseismologists with the first significant high precision photometric data set with high time resolution and good statistics. This will provide a new understanding of stellar structure including determination of mass, age, helium abundance, and convective mixing length. Asteroseismology information for O, B, and A stars can be obtained if a subset of these stars is added to the main sequence dwarf target stars of FRESIP.

II. STELLAR VARIABILITY

Monitoring of stellar variability at all time scales will be a natural outcome of the FRESIP mission. The data set can also provide photometric information on various types of variable stars in the field of view such as δ-Scuti stars and RR Lyra stars if these are included in the target list. The FRESIP platform is particularly useful for monitoring eruptive variables such as cataclysmic variables, novae, and flare stars.

Cataclysmic variables (CVs) illustrate the types of science that can be done with FRESIP. CVs are stellar systems with a white dwarf primary and a K or M star secondary undergoing mass transfer to the white dwarf; there are about fifteen known CV stars in the proposed FRESIP field of view. Observations of CVs on one to ten minute timescales will provide information on accretion disk physics, magnetic field strength, and rotation rates, as well as asteroseismology of the secondary star. Observations with timescales of hours to days will provide orbital periods, information on mass transfer rates, and observations of the stars before outburst. Many CVs are observed from the ground after an outburst, but little is known about the pre-outburst condition or the character of the outburst itself due to the fast rise time. The continuous nature and long baseline (six years) of the FRESIP data provide a unique platform for these observations.

III. EXTRAGALACTIC OBJECTS

While the current theoretical understanding of the variability of active galactic nuclei (AGN) such as quasars, blazars, and BL Lacertae objects does not justify an AGN specific mission, much can be learned about AGN variability by using an unmodified FRESIP platform.

Calculations indicate that we can expect about 300 AGN with $m_v < 20$ in the FRESIP field of view. The current design of FRESIP will allow for one percent photometry of these objects without modification of the optics, focus, or integration time. The long term continuous photometric measurements will provide a wealth of information on the broad band variability of AGN at all frequencies from hours to years. These observations will undoubtedly lead to improvement of theoretical models and a better understanding of AGN.

The Editors
January 1994

FRESIP Astrophysics Workshop (photograph)

Back row (left to right): E. Dunham, D. Soderblom, R. Radick, H. Reitsema, S. Brandmeier, A. Granados, R. Dempsey

Middle row (left to right): D. Koch, B. Haisch, R. Gilliland, B. Peterson, D. Gies

Front row (left to right): T. Brown, P. Milford, B. Borucki, S. Howell

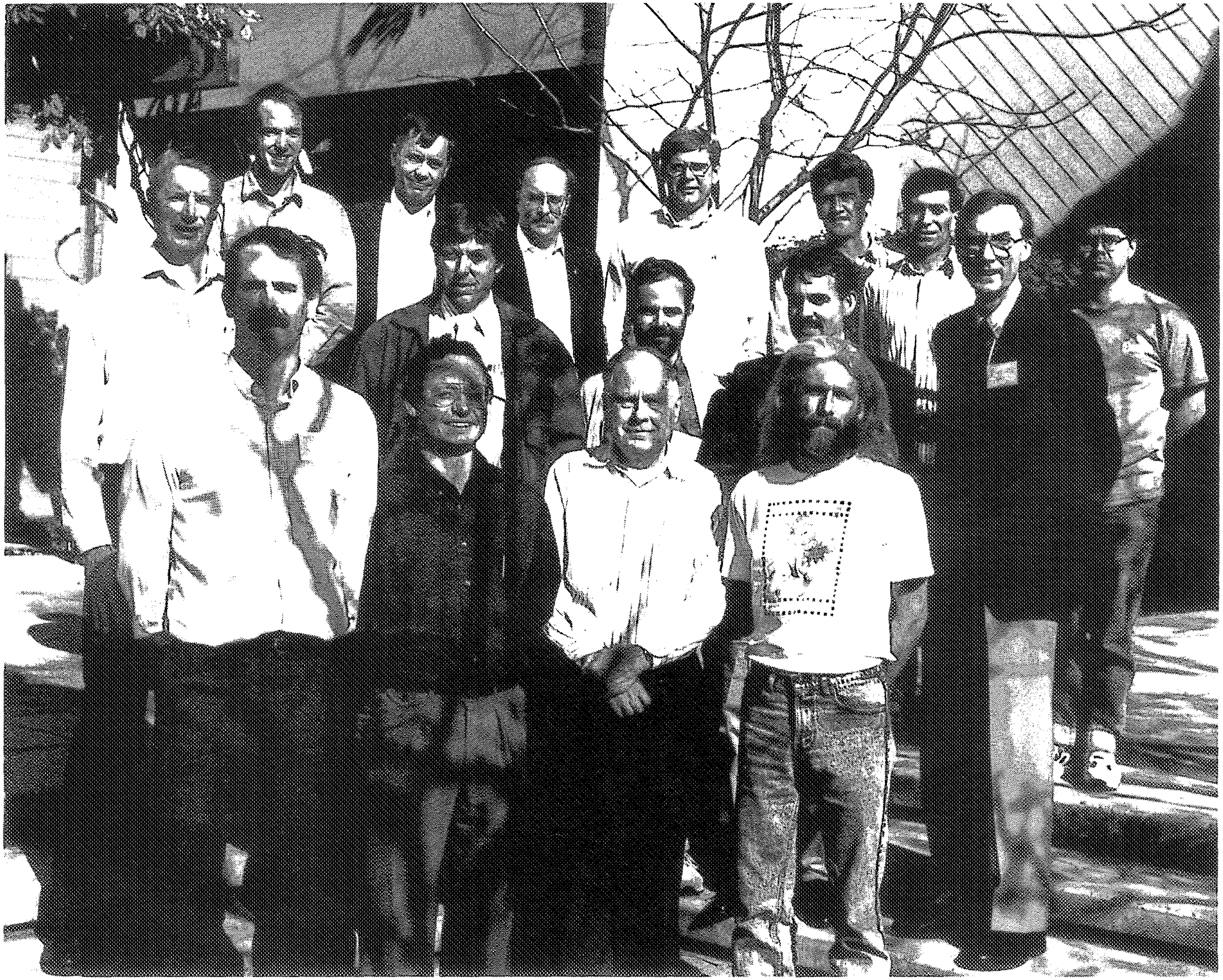

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Table of Contents

I. SOLAR AND STELLAR PHYSICS

II. STELLAR VARIABILITY

III. EXTRAGALACTIC OBJECTS

Summary

The FRESIP research team in collaboration with many respected researchers in the fields of stellar and extragalactic astrophysics have produced a candidate list of important astrophysical research which can be done within the context of the FRESIP mission. FRESIP provides a unique opportunity for study of stellar seismology and evolution as well as the study of variability of both stars and AGN. This "auxiliary" science can be performed with only minor changes to the basic FRESIP mission design, and will provide the astrophysical community with an unprecedented data set without compromising the integrity of the mission design, or diminishing FRESIP's prime goal; the discovery of Earth-sized inner planets and the investigation of solar system formation theory through the determination of the frequency of such planets.

Acknowledgments

The success of the FRESIP Astrophysical Workshop was due primarily to the effort of the participants; we thank them for their valuable contributions and scientific insight. We also thank Thomas Pierson, Janel Griewing, Michelle Murray, and the staff of the SETI Institute for their assistance with logistics and organizational details without which we could not have held the workshop.

Workshop Participants

William Borucki (FRESIP PI – NASA/ARC), Stefan Brandmeier (Technical University of Konstant), Timothy Brown (High Altitude Observatory), William Cochran (University of Texas), Robert Dempsey (Space Telescope Science Institute), Edward Dunham (NASA/ARC), Douglas Gies (Georgia State University), Ronald Gilliland (Space Telescope Science Institute), Arno Granados (SETI Institute), Bernard Haisch (Lockeed Palo Alto Research Labs), Steve Howell (Planetary Science Institute), David Koch (NASA/ARC), Peter Milford (Stanford University), Bradley Peterson (Ohio State University), Richard Radick (USAF Phillips Laboratories), Harold Reitsema (Ball Aerospace), and David Soderblom (Space Telescope Science Institute).

I. SOLAR AND STELLAR PHYSICS

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STELLAR ACTIVITY: ASTROPHYSICS RELEVANT TO GLOBAL CHANGE

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ABSTRACT

FRESIP will obtain a great deal of data on stellar activity and flares on F, G and K dwarfs. Rotation periods, flare distributions and possibly stellar cycles will emerge. This apparently curiousity-driven research actually has implications for our understanding of global climate change. Significant climate change during the seventeenth-century Maunder Minimum is thought to be related to a change in the solar condition. Recently acquired data from the Greenland Ice-core Project suggest that far greater climate changes on decade time scales may have occurred during the previous interglacial. It is possible that a yet more drastic change in state of the Sun was responsible. We have no relevant solar data, but can begin to explore this possibility by observing an ensemble of solar-like stars.

1. SOLAR VARIABILITY AND GLOBAL CHANGE

While the variability of the Sun on time scales ranging from seconds (flares) to weeks (active regions) to years (sunspot cycle) has been known and recognized for decades, it has only been in the past 20 years or so that we have learned that this is only one of at least two, and perhaps more, states that the Sun may be in. We now know that from about 1640–1715 AD the Sun was in a significantly different state known as the Maunder Minimum, and that this state was associated with a major climate change called the "Little Ice Age." During these decades, winters in Europe (and presumably elsewhere) were significantly more severe than at present: ice was a problem on the Thames, Baltic seaports were frozen over for several weeks longer than before, glaciers in the Alps grew in size, etc. (see Noyes 1982).

The "Little Ice Age" clearly had significant consequences. However at this time we still do not know what the actual global temperature change amounted to in comparison to that of today. Estimates range from a mere 0.4 C to as much as 1.5 C (see Noyes 1982, Baliunas and Jastrow 1990 and references therein). The corresponding change in the solar constant may have been as little as 0.22 percent or as much as 0.75 percent.

Moreover a variation in the local irradiance is not the only factor at work in climate change. Numerous secondary influences are also liable to be important. For example, the height of the troposphere is known to be sensitive to seasonal changes in solar flux due to the earth's orbital eccentricity. Changes in atmospheric circulation are thus likely to result from changes in the solar irradiation. In this way, rainfall and snowfall patterns, for example, could vary with a change in the solar constant.

Radiocarbon records suggest that over the past few thousand years the Sun may have spent perhaps one-third of its time in a Maunder Minimum-like state.

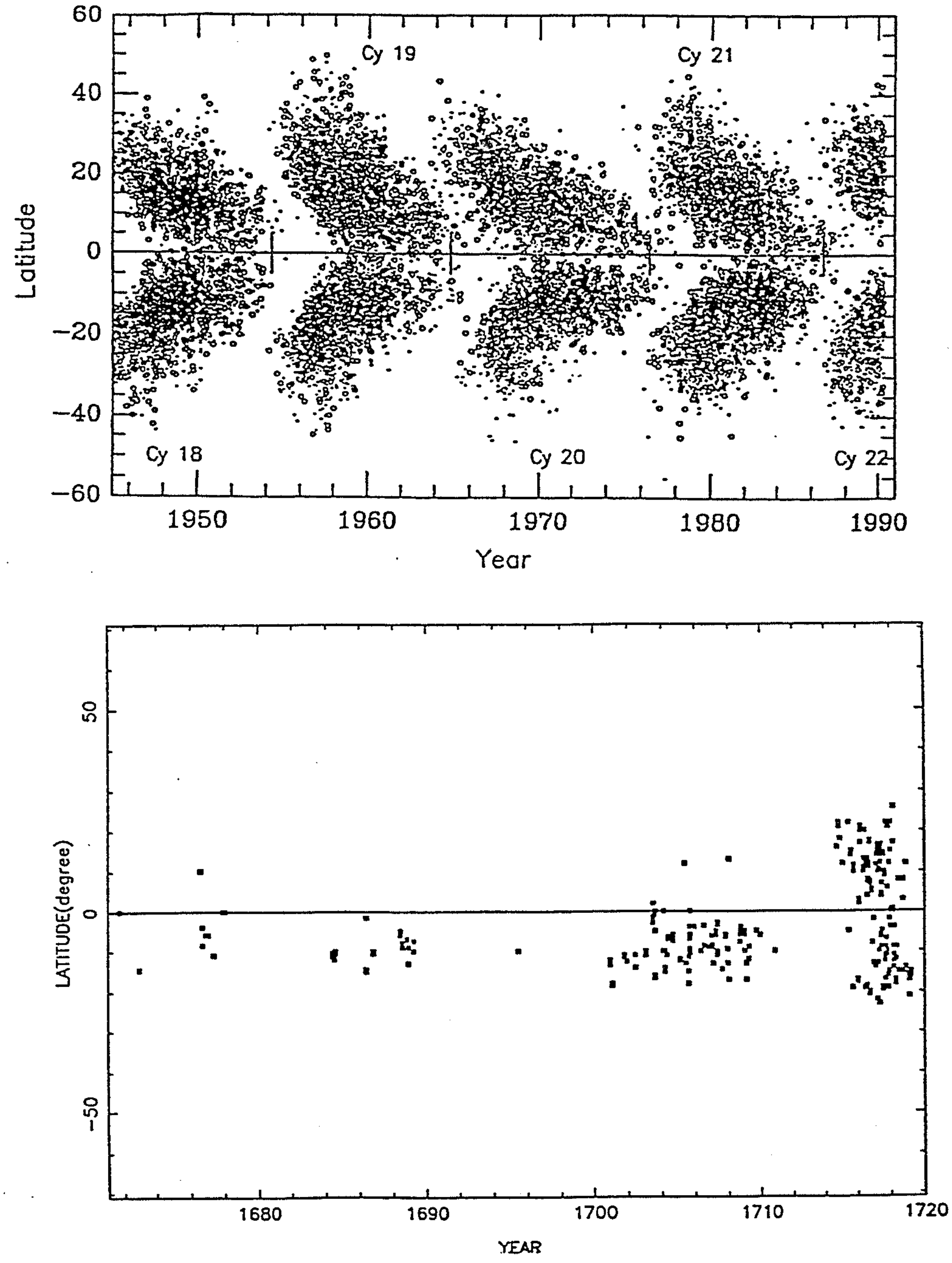

Figure 1. (top) Butterfly diagram of sunspots from the modern era showing parts of the five current solar cycles. (bottom) The same diagram during the Maunder Minimum inferred from observations at the Observatoire de Paris from 1660 to 1719. (from Ribes and Nesme-Ribes 1993)

As significant as the Little Ice Age may have been during relatively recent times, that change in climate phase pales in comparison to recent evidence from the Greenland Ice-core Project (GRIP 1993, White 1993). Civilization has arisen in the 10000 years that the earth has now been basking in an interglacial period. How stable is our interglacial climate? The new GRIP data suggest up to 10 C changes in temperature on a time scale of perhaps

5–20 years (!) from time to time during the last interglacial (Eemian) period some 115000 to 135000 years ago. Such a fluctuation today would have catastrophic consequences on societies, economies and eco-system. Unfortunately there is no solar data whatsoever to correlate with this huge climate perturbation. It is certainly suggestive that an even more dramatic change in the Sun than the Maunder Minimum may have occurred.

We are extemely limited in our ability to study the Sun on long time scales. However with FRESIP we can examine many other stars like the Sun and in effect study the sun in time by observing the distribution of activity states of solar-like stars.

Figure 1 (from Ribes and Nesme-Ribes 1993) is a butterfly diagram of the solar cycle reconstructed from 8000 daily observations made at the Observatoire de Paris from 1660 to 1719, i.e. during most of the Maunder Minimum, in comparison to the past fifty years. Sunspots were quite rare.

How do other stars come into play? The Mt. Wilson multi-year monitoring of Calcium H and K line indices of solar-like stars (see Baliunas and Vaughan 1985 and references therein) has resulted in an apparent correlation between low Ca index and lack of stellar cyclic variation, as in the case of the Sun during the Maunder Minimum. Moreover it appears that solar-like stars exhibit a somewhat bimodal distribution in the Ca index suggestive of two activity states analogous to the Maunder-minimum Sun and the "normal" Sun (Baliunas and Jastrow 1993).

We may thus be able to understand the states of the Sun in time (which may well be more than two) by studying the present distribution of spottedness of an ensemble of solar-like stars. On a multiyear time scale we may even be able to catch a star in transition from one phase to another.

Such a study of stellar activity is clearly more than simply curiousity driven research. Our ability to understand our own global environment may depend on how well we learn to interpret apparently subtle changes and differences in other stars.

2. ACRIM SOLAR OBSERVATIONS

The Active Cavity Radiometer Irradiance Monitor (ACRIM) onboard the Solar Maximum Mission obtained absolutely calibrated solar bolometric flux measurements with 131 s sampling over most of a solar cycle (1980–1989) (see Hudson 1988, Willson 1994). Measurements with this instrument produced the first unequivocal detection of total (bolometric) solar irradiance variability. Figure 2 shows a dip in the irradiance coinciding with the passage of a sunspot group across the disk. This is not a unique event. Daily averages during 1980 show numerous dips associated with passage of spot groups as shown in Figure 3 (top).

Upon examining the light curves of Figures 2 and 3 more carefully one finds that there are enhancements of the flux as well as dips. In fact the enhancements often show up as "wings" on either side of sunspot deficits. Enhancements are due to increased emission from active region plage and faculae. In an idealized situation consisting of a single active region one would first measure an enhancement as plage and faculae surrounding spot groups rotate onto the visible hemisphere; as the spots appear the light curve would begin to dip, reaching a minimum as the active region/spot group transits the central meridian

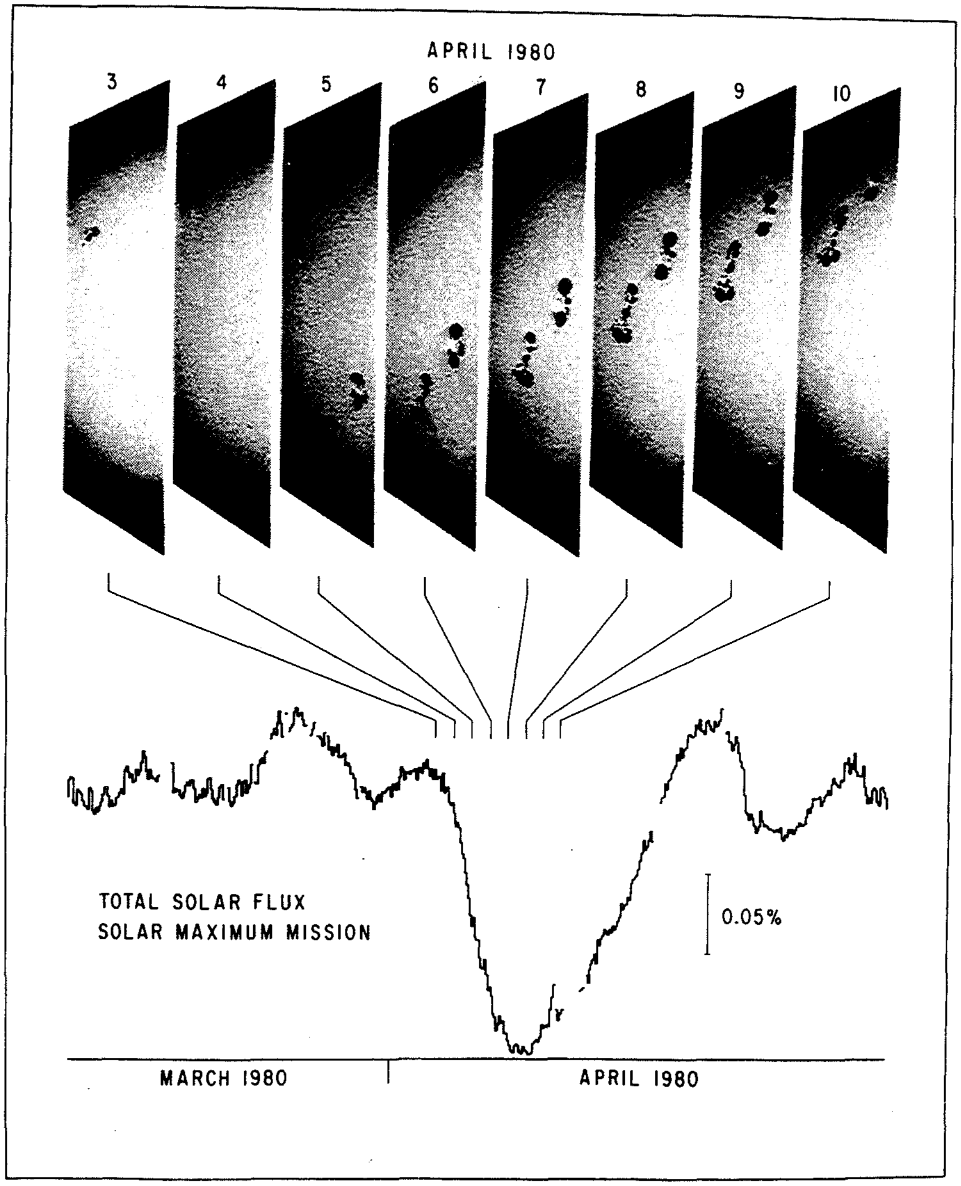

Figure 2. ACRIM observations showing a dip in the irradiance coinciding with the passage of a sunspot group across the disk. (from Noyes 1982, courtesy of H. Hudson)

with maximum projected area, and the process would reverse as the active region rotates off the visible hemisphere.

Overall, one finds that sunspot deficits appear with amplitudes of up to 0.15 percent and that emission increases up to 0.1 percent are attributable to plage and facular excesses resulting from the presence of active regions.

Models have been developed that can accurately (10–20 percent) relate the bolometric flux changes to areas covered by sunspot and plage/facular brightening. Figure 4 from Chapman et al. (1992) illustrates this. Ground-based photometric imaging can be used

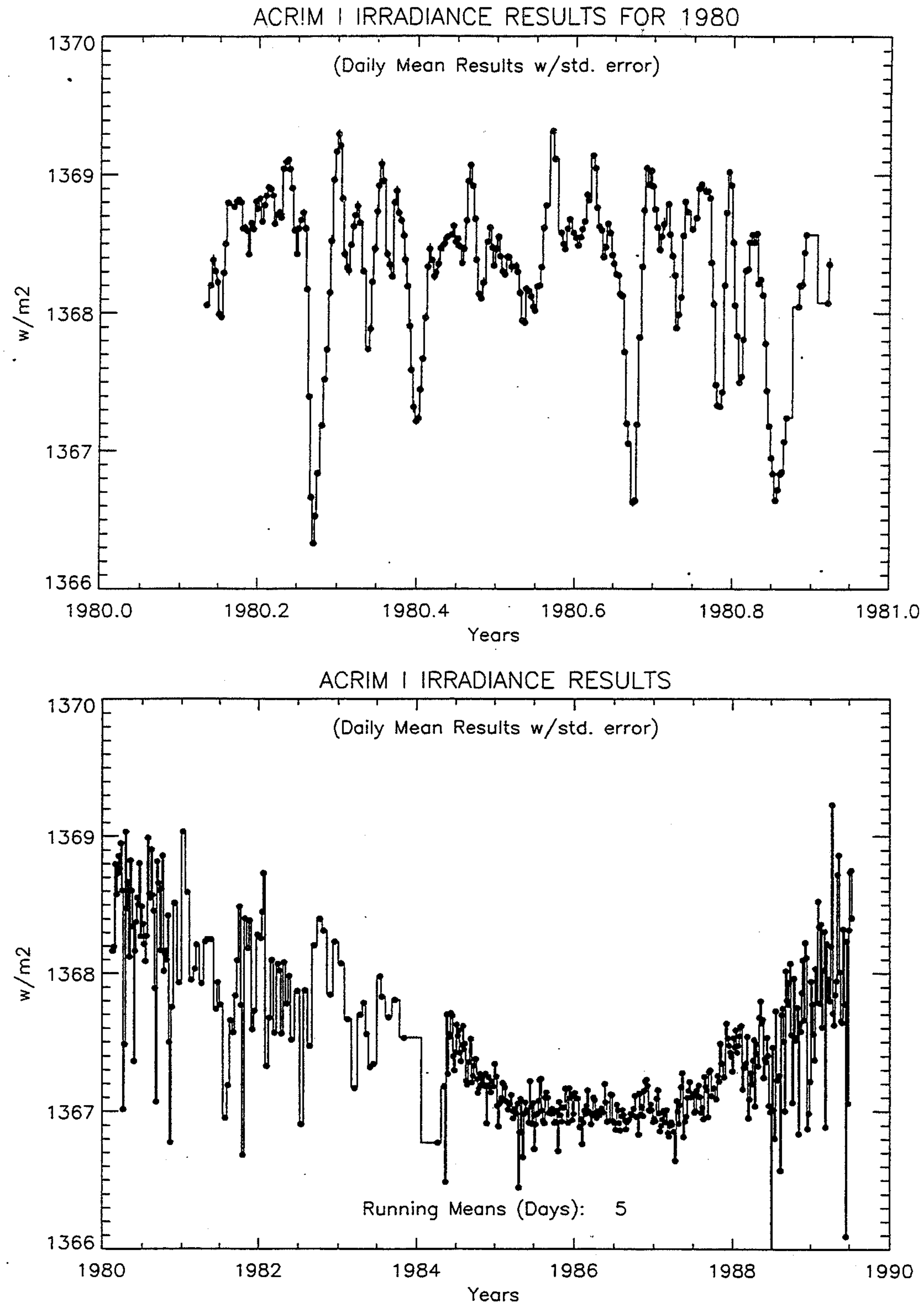

Figure 3. (top) ACRIM observations of daily mean solar bolometric irradiance during 1980. (bottom) The solar irradiance over the declining phase of cycle 21 from the time of launch of SMM (February 1980) through the maximum phase of cycle 22 (July 1989) until the reentry of the satellite (December 1989). (from Willson 1994)

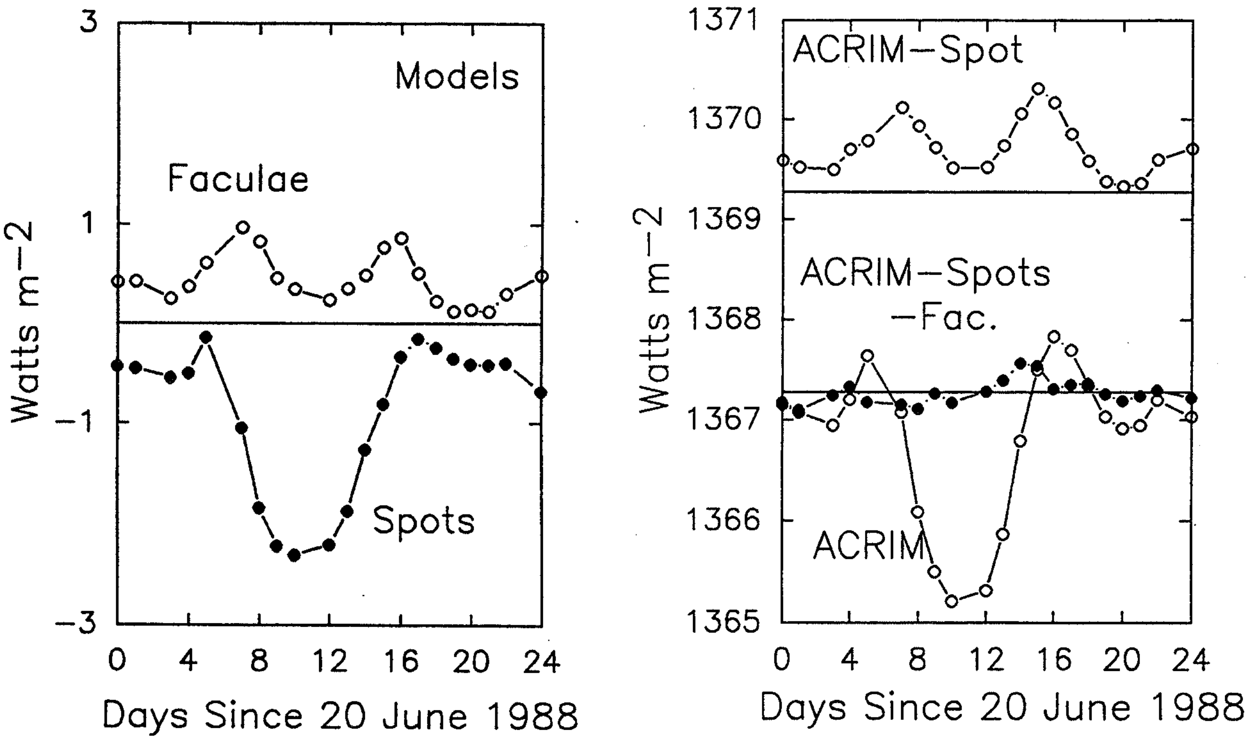

Figure 4. (left) Modeled facular excess and sunspot deficit calculated from ground-based two-color photometric images of the Sun from June 20 to July 14, 1988. (right) Application of this model to the ACRIM observations. Shown are the ACRIM signal, the (ACRIM—Spot) model, and the (ACRIM—Spot—Faculae) model, which results in a flat corrected signal. (from Chapman et al. 1992)

to estimate the projected areas covered by spots and faculae resulting in a photometric facular index (PFI) and a photometric sunspot index (PSI). An empirical formula relates the bolometric irradiance changes to these two indices. There is a third contribution from the overall bright network, but this varies mostly on a solar cycle time period, not on a solar rotation period. The overall solar irradiance variations can be quite well accounted for by facular/plage brightening and sunspot darkening. For example, the relationship between increasing PSI and total irradiance decrease is shown in Figure 5.

Figure 3 (bottom) shows the ACRIM data over the declining phase of cycle 21 from the time of launch of SMM in February 1980 through the maximum phase of cycle 22 in July 1989 until the reentry of the satellite in December 1989 (from Willson 1994). The overall solar cycle change is seen to be about 0.15 percent.

These ACRIM observations reflect the absolute minimum level of variability of the Sun in that they account for the entire solar spectrum. In specific bandpasses the Sun can be highly variable: several orders of magnitude in X-rays during flares, about an order of magnitude in non-flaring X-rays over a solar cycle, factors of two or three in the ultraviolet. No measurements at the ACRIM-precision level exist for the Sun solely in the optical, i.e. a FRESIP-like band. Presumably variations could be a factor of two or more enhanced over the bolometric ACRIM variations.

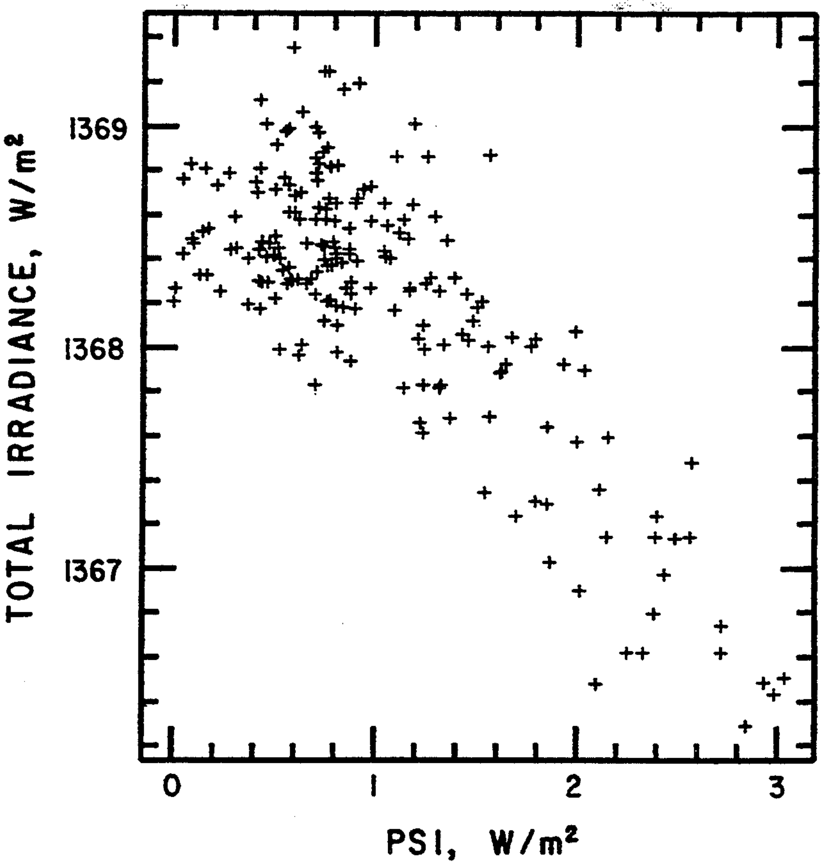

Figure 5. Correlation between increasing sunspot area as measured by the photometric sunspot index (PSI) and decreasing solar irradiance as measured by ACRIM. About half the ACRIM variation is adequately accounted for by the PSI changes. (from Hudson 1988)

3. STELLAR VARIABILITY

Significantly greater changes are expected and have been seen on other stars, with up to 10–100 times the range of the solar variability. It should be easily possible to obtain stellar rotation periods from analysis of such data for a significant fraction of the FRESIP sample. Over a 6 year mission stellar cycle variations should also be measureable in many cases.

Figure 6 shows an example of major stellar variability over a broadband. Hartmann et al. (1981) used the Harvard archival plate collection to examine the B−band behaviour of the dK5e star BD +26°730 going back to the turn of the century. The old data were, of course, photographic, but have been converted to the standard Johnson photometric B−band. The star is thought to be viewed pole-on, thus eliminating any rotational modulation which would obscure the long-term cyclic variability.

More detailed discussion of stellar activity related variability observations and modeling may be found in the contributions by Dempsey and by Radick in these proceedings.

4. FLARES

White light flares on the Sun are short-lived (typically a few minutes) and cover a small

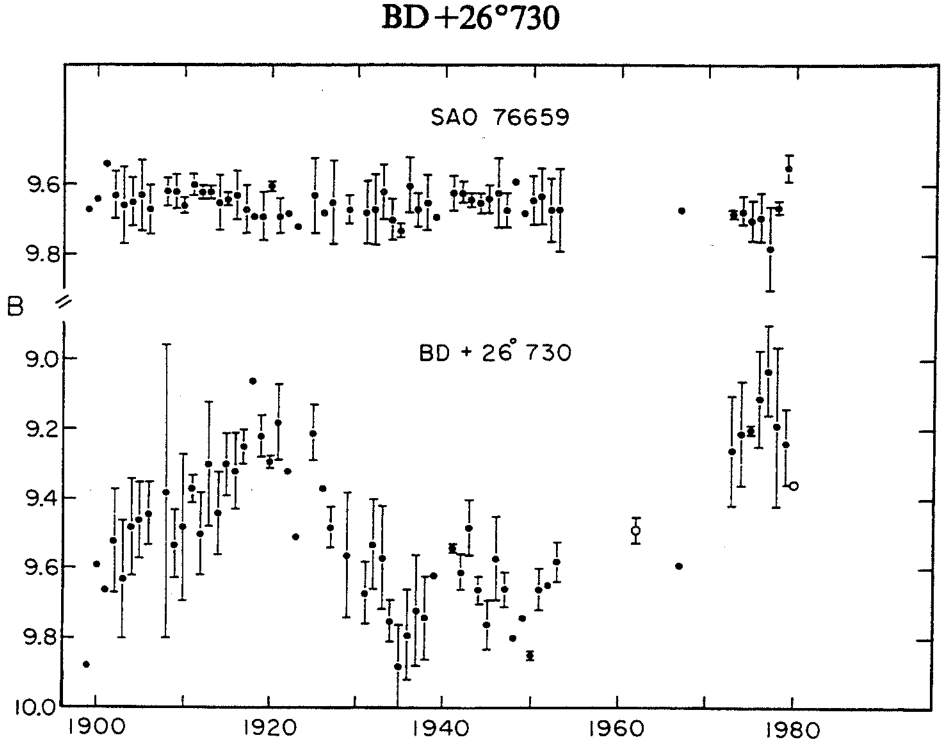

Figure 6. Long-term variability of the dK5e star BD+26°730 referenced to a nearby comparison star. (from Hartmann et al. 1981)

area on the Sun (see Haisch, Strong and Rodonò 1991 for a review of solar and stellar flares). The most energetic solar white light flare amounted to $\sim 2 \times 10^{29}$ ergs s^{-1}, which is only 0.005 percent of the bolometric luminosity, $L_{\odot} = 3.8 \times 10^{33}$ ergs s^{-1}. Note that the $V-$band luminosity is much less than the bolometric: $L_V = 0.12 L_{\odot}$, and so depending on the actual white light band used to detect the flare, the change could be several times higher than 0.005 percent. However ACRIM did not, in fact, detect any solar flares.

Many late-type main sequence stars exhibit much more energetic flaring than the Sun. Figure 7 is an example of two stellar flares. The AD Leo flare was part of a coordinated. multiwavelength observing campaign by Rodonò et al. 1994. The AD Leo flare is on an arbitrary scale, but the actual peak was $\Delta U = -2.1$ mag, i.e. a factor of 7 increase in brightness. The brightest, impulsive part of this flare lasts less than 100 s.

The optical flare radiation is very approximately similar to photospheric radiation from a 25000–30000 K star, i.e. like a B-star with $(U - B) = -1$ and $(B - V) = -0.3$, with a bolometric correction of $BC = -2.8$. The colors of a star like AD Leo are $(U-B) = +1.55$, $(B - V) = +1.25$. From these colors we can estimate the corresponding ΔV for this event: $\Delta V = \Delta U + (U - B)_* + (B - V)_* - (U - B)_f - (U - B)_f = 2.0$, i.e. in the $V-$band the flare would be two magnitudes fainter than the star, corresponding to a brightness change of around 16 percent.

There are also observations of dips in the optical emission associated with flares, and these are taken as evidence of prominence eruptions or other mass ejections associated with flares. Such an example is shown in the EQ Peg flare. According to Giampapa et al. "...the brightness of the star decreases at roughly 0.1 mag per minute for 2.7 minutes,

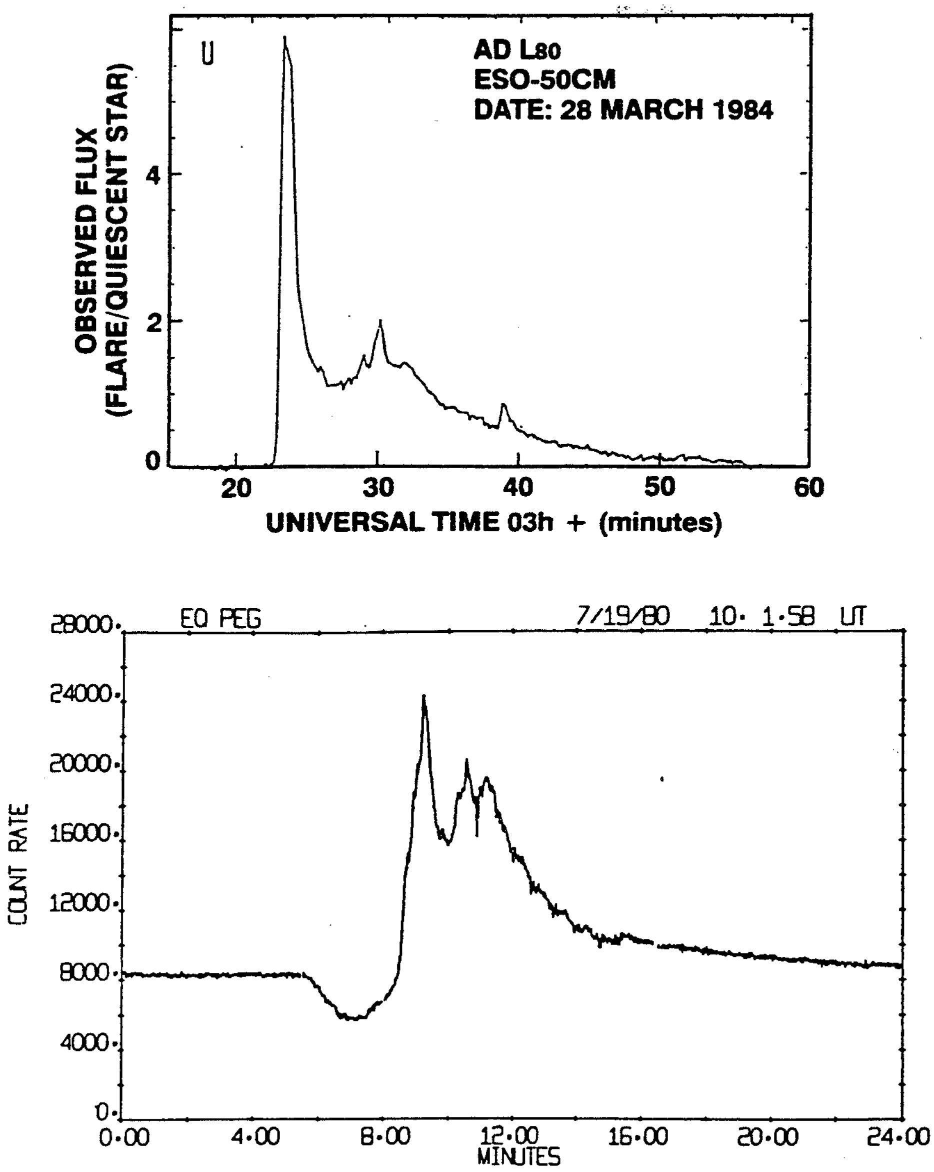

Figure 7. U—band flares on AD Leonis and EQ Pegasi (from Giampapa et al. 1982).

then levels off at 75 percent of the quiescent brightness for 1 minute before the flare begins.

Moreover there are relations between the energy of a flare and the frequency of occurrence: $E(\nu)$. As a first approximation, the $E(\nu)$ relation has the same shape but a different overall level from stars of differing activity states, i.e. $E(\nu) \sim 10^4 E(\nu)_\odot$ for some very flare-active stars. This guarantees that FRESIP will see many optical flares with flux changes exceeding several percent on time scales of minutes. Determining the $E(\nu)$ function for hundreds of flaring stars should give us a valuable constraint on coronal heating mechanisms.

ACKNOWLEDGEMENTS

This work was supported in part by the Lockheed Independent Research Program.

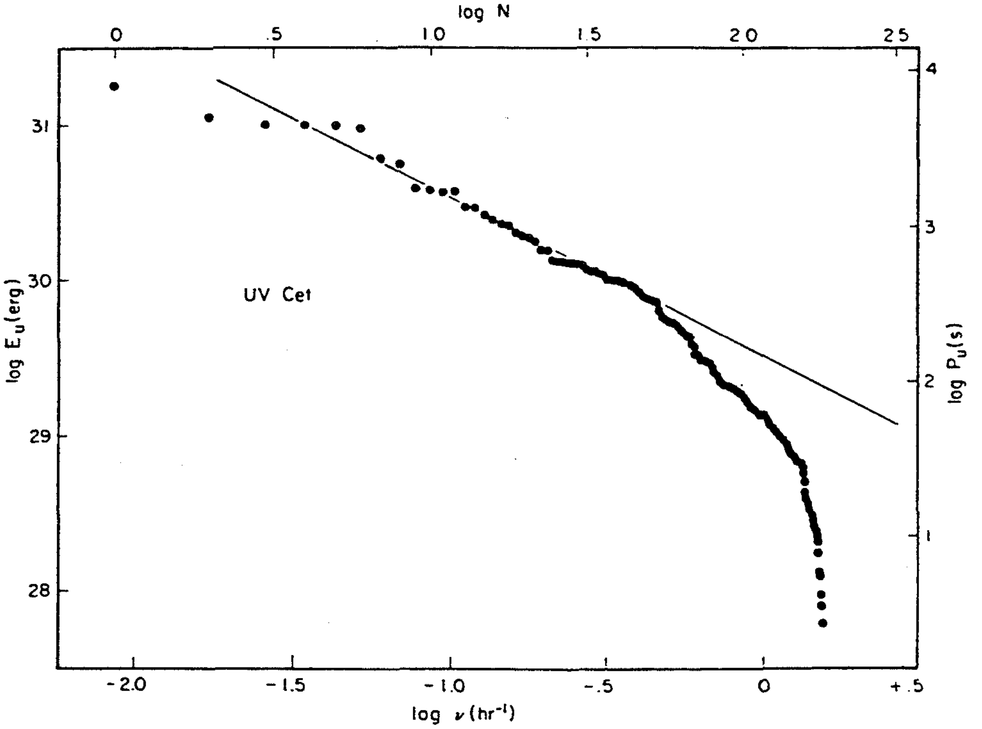

Figure 8. Cumulative frequency diagram of total flare energy vs. occurrence rate. (from Lacy et al. 1976)

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Probing Surface Structure on Late-type Stars With FRESIP

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Abstract.

We discuss possible secondary scientific results obtainable with the FRESIP satellite in regards to surafce features on solar-like stars.

1. Introduction

Currently, for only one star, our Sun, is it possible to resolve surface features such as sunspots and plages. In the case of the Sun these features are well studied. For example, it is clear that the dark sunspots never cover more than 1% of the surface and tend to develop at mid latitudes with formation occurring closer to the equator as the 11-year solar cycle progresses. Through the remarkable work of the Mt. Wilson project we now know many stars possess surfaces covered unevenly with plage-like regions (Wilson 1978) and that stellar activity levels may undergo cyclic variations similar to the solar cycle (Baliunas & Vaughn 1985). Noyes et al. (1984) demonstrated the connection of the Ca II emission flux to the magnetic dynamo believed to be operating in rapidly rotating, convective stars. In general, the Ca II emission is strongest for stars with $P_{rot} \approx$ 1-3^d and gradually decreases as P_{rot} increases. Similar relationships have been observed in other diagnostics (e.g., Simon & Fekel 1987; Strassmeier et al. 1990) and the rotation-activity relationship is now firmly established, at least for single stars.

Numerous late-type stars show photometric amplitude modulation which is believed to result from large, sunspot-like regions rotating in and out of view as the star rotates. The light curves of a few dozen stars have been modeled successfully using simple spot models (see Dempsey et al. 1992 for references). Results from modeling the photometric variations have been supported by high resolution spectroscopic studies, called Doppler imaging, for a very small subset of systems ($<$ 12) and for a very few epochs. However, since good phase coverage is required and large amplitude photometric variations are easier to detect, these studies have been biased towards the short-period "hyper-active" systems. Furthermore, all stars studied in this manner have been relatively bright which usually means they are giant systems. Results from these studies are rather puzzeling since the detected spots are almost always at or near the pole, quite unlike the case of the Sun where spots tend to form closer to the equator. Does this result from studying only the "hyper-active" systems or is the Sun unusual among late-type stars? Or, perhaps, is the Sun going through some phase where its spot behavior deviates from the "norm", whatever that may be? More systems must be studied to answer these questions.

2. FRESIP

A major benefit of the FRESIP project will be the ability to detect and monitor surface features *on thousands of stars.* An immediate result of this is that a statistically significant number of stars of all spectral types can be sampled. Since the program stars will be dwarfs this will allow us to study the advent of spots in objects earlier than the Sun and to see how far down the main sequence such phenomena persist, i.e. do fully convective M stars posses spots. If possible, it would be desirable to include a sample of 200-300 class IV and III objects. This allows us to probe the characteristics of the future Sun.

In particular, surface features on the longer period ($P > 10 - 20^d$), less active systems will be studied in detail for the *first time.* This results from the fact that FRESIP will be able to detect photometric variations with periods greater than several weeks more easily than can be done from the earth. Earth based observations are limited by short observing seasons, weather and evolution of the surface features on timescales less than P_{rot}. A typically poor light curve is shown in Fig 1. Since it has also been established that the rotation period generally determines the activity level, the longer period systems will be less active and more solar-like than those studied to date. Therefore, the millimag precision of **FRESIP will allow us to probe to lower thresholds, i.e, smaller spot or plage areas, available from the ground**. The short period systems, and those with large photometric amplitudes, will be studied in greater detail than available using ground based photometers. This will allow the study of changes on very short timescales if present.

3. Simulations

To simulate some possible results we used the DOPPEL code discussed in Dempsey et al (1992) modified to yield the integrated magnitude over the 450 - 700 nm bandpass of the FRESIP satellite. The models simulated G and K dwarfs and a K giant. Only spots cooler than the photosphere were simulated since warmer areas will have similar results. Also, real life is far more complicated than the models presented here. In general it is likely that several cool spots will be present along with hot regions thus making the light curve rather complicated. However, we can use experience gained from modeling RS CVn systems (e.g., Strassmeier 1988; Strassmeier et al 1988; Jetsu et al. 1990; Dempsey et al. 1992, 1993) and concentrate on what new is detectable. The models assume a single, square spot with a temperature several hundred degrees lower than the surrounding photosphere. Note, we can only detect *assymmetries* in the spot/plage distribution since a unform spot, e.g., an equatorial belt, will affect the light curve equally at all phases. Furthermore, the detection threshold for our work can be increased easily by binning the data. For example, consider a star with a rotation period of 33 days. We could bin 8 hours of data into steps of 0.01 in phase with an accuracy of 0.001 mag/ sqrt(8) or 0.0004. Even with such large bins we will have better phase coverage than achieved from the ground.

For a G dwarf it is possible to **easily** detect spots with a surface area covering $\approx 0.04\%$ of the total surface without binning the data (Fig 2). To date the smallest coverage measured on a star other than the Sun has been about 5%. Therefore it is clear that we will, for the first time, be able to detect solar-like spots which have never covered more than 1% of the Sun! Similar limits are found for the K dwarf and giant models differing due to contrast effects and spot brightness relative to total brightness. Binning the data as well as using readily available period finding algorithms well allow detection of features covering $< 0.1\%$.

4. Discussion

Question we hope to address with this project for the first time:

- Do the long period stars have spots like the Sun does, i.e. as we go to longer and longer period systems will we observe a continuous spectrum of smaller and smaller spot coverage?
- What is the statistical properties of surface features on G and K dwarfs. Since the convection zone depth is a critical parameter in dynamo theory we would expect to see differences, e.g., size, between spectral types.
- Do all stars have the same magnitude and direction of differential rotation as does the Sun? As indicated in Fig 3, we can also measure differential rotation on a number of stars by observing the change in period as the spots evolve to different latitudes. Preliminary results from Doppler imaging has shown conflicting results but there are only a couple of systems with adequate data.
- Is there any relation between the area spot coverage and the rotation period or cycle period? For example, do stars with small spot coverage tend to have longer cycle periods than those with large spots? It will not be possible to to measure cycles longer than 5-6 years but some of the "hyper-active" stars might have periods measurable in the lifetime in FRESIP.
- How do spots evolve on rotation and cycle times scales? Limited evidence exists that spot may stay stable for many rotation periods or change daily (Dempsey et al. 1993).

What is important to realize is **none of these questions can be answered with ground based instruments.**

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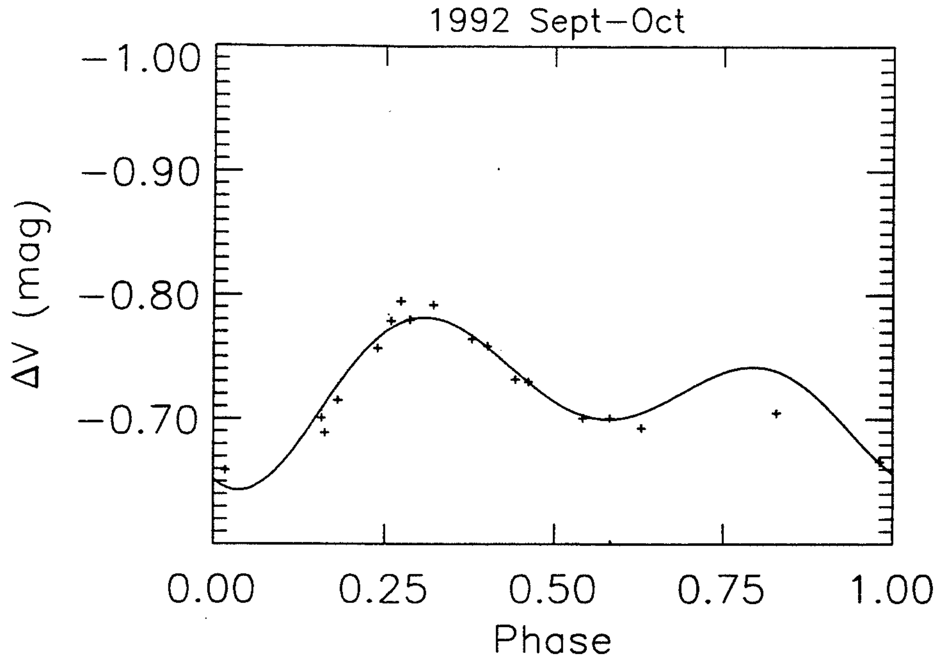

FIGURE I The measured light curve for IM Peg (Dempsey et al. 1993). Individual observations are indicated by plus signs. A model is shown by the solid line. Note the poor sampling, especially in the later portion of the light curve.

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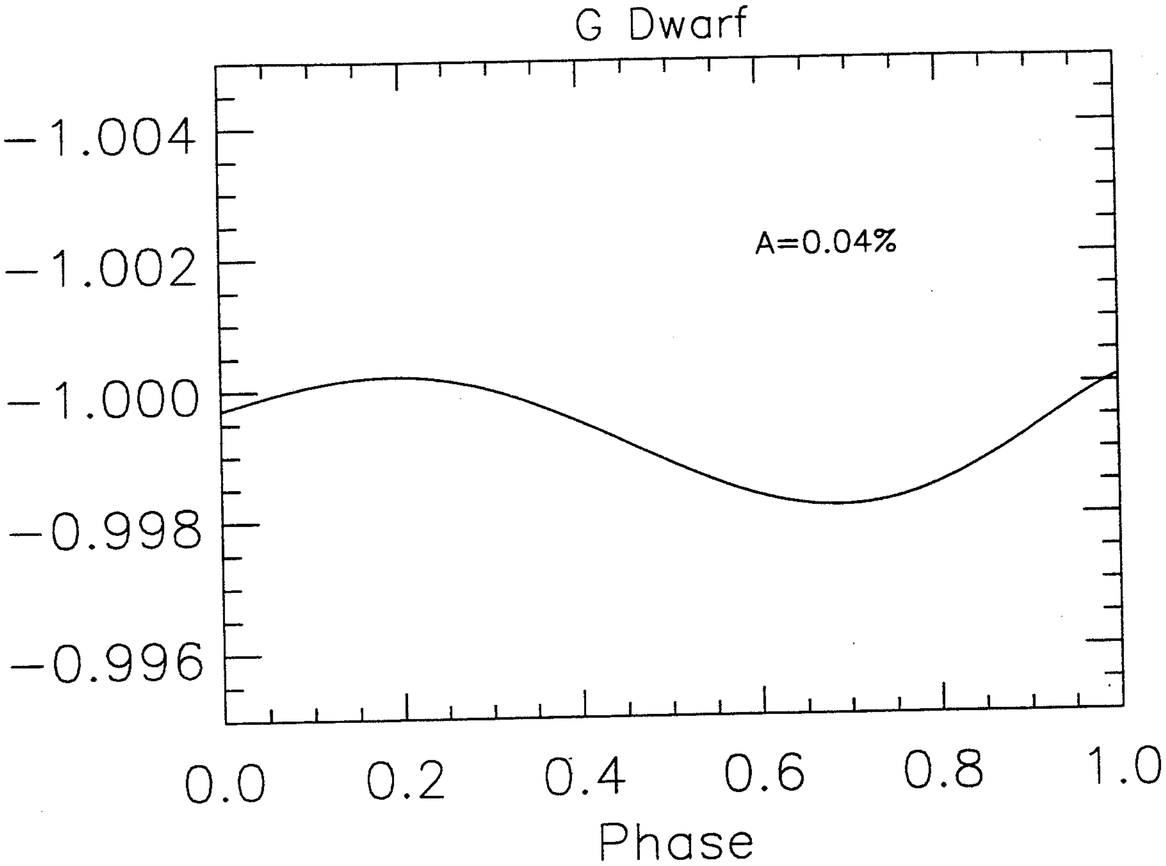

FIGURE II The predicted light curve of a G dwarf. Parameters used are: $T_{photosphere}$ = 5800K, T_{spot} = 3800, radius = 1 R_o, inclination = 45 degrees. A single spot with an area of 0.04% was placed arbitrarily on the surface. The y-axis is in magnitudes. The amplitude is approximately 0.002 mag and would be easily detectable with the FRESIP satellite.

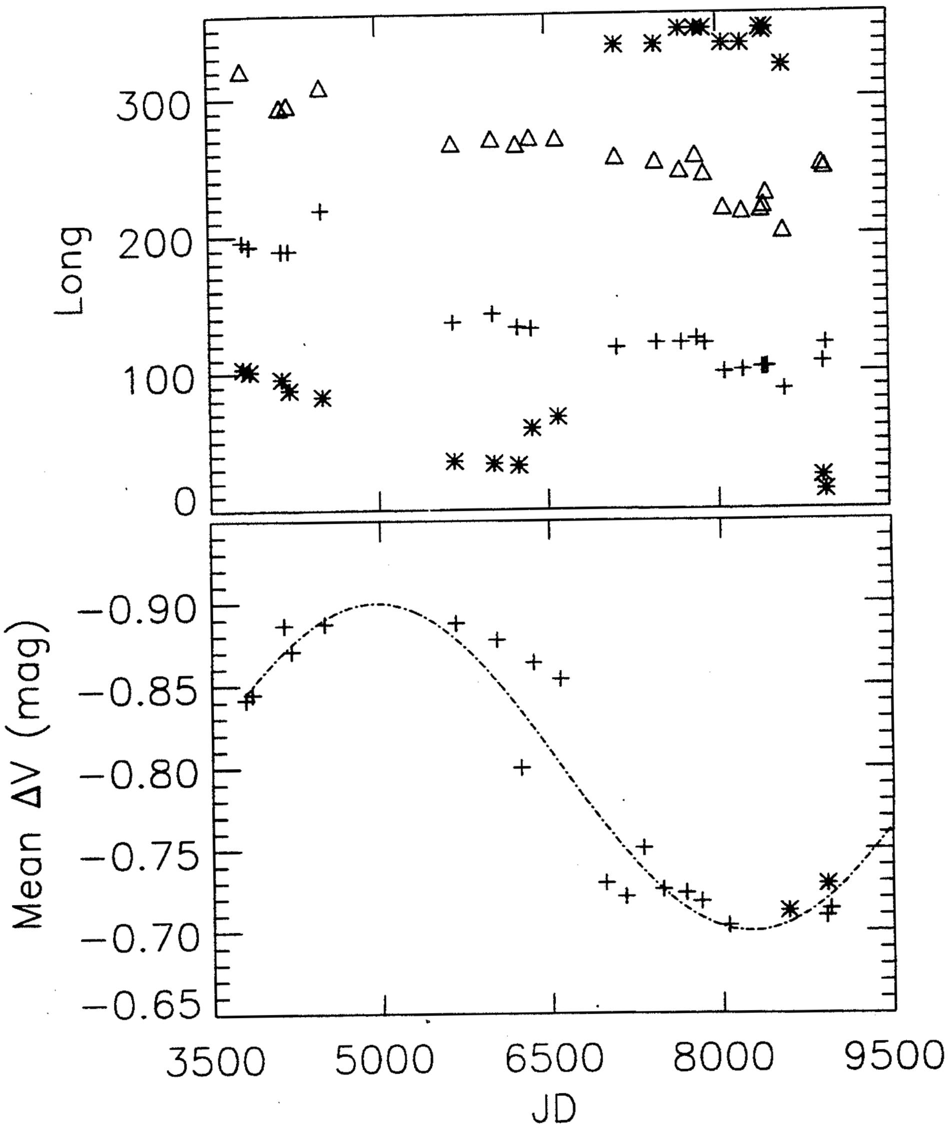

FIGURE III Longitude of spots (top) and mean brightness (bottom) on IM Peg over 15 years. This illustrates that while we know spots evolve on long timescales the information is rather poor.

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ASTEROSEISMOLOGY – THEORY AND PHENOMENOLOGY

p. 10

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I. Introduction

Asteroseismology is commonly understood to mean the study of normal-mode pulsations in stars that, like the Sun, display a large number of simultaneously excited modes. The idea of learning about a physical system by examining its oscillation modes is of course an old one in physics, but it is only fairly recently that data of sufficient quality have become available to apply this technique to stars.

The Sun is (and will likely remain) the outstanding example of the progress that can be made using seismological methods. Seismic studies of the Sun have succeeded in mapping the variation of sound speed with depth in the Sun, and the variation of angular velocity with both depth and latitude; they have measured the depth of the Sun's convective envelope, and they have begun to be used to estimate the helium abundance in the convection zone and to reveal at least some of the subsurface structure of solar activity.

Many stars besides the Sun may be also be amenable to asteroseismic analysis. Stars of roughly solar type should of course behave in ways similar to the Sun, and stars of this sort form a large fraction of the potential targets for asteroseismology. But several other kinds of star (δ Scuti stars, roAp stars, and the pulsating white dwarfs) also have the desired pulsation characteristics. Pulsations in some of these stars are, for various reasons, much easier to observe than in the Sun-like stars; indeed, to date virtually all unambiguous observations of multi-mode pulsators relate to these other categories of stars.

Regardless of the type of star or the mechanism driving its pulsations, we will not in the foreseeable future have as much pulsation information about other stars as we have about the Sun. A very large majority of the 10^7 modes seen in the Sun have horizontal wavelengths that are a small fraction of a solar radius. When averaged over the solar disk (as a distant observer would do), the perturbations due to these modes average to zero, rendering them undetectable. It is only in special circumstances that modes with angular degree greater than about 3 are observable on distant stars; the number of modes that may be observed is therefore likely to be at most a few tens. Nevertheless, since oscillation mode frequencies are arguably the most precise measurements relating to a star that we can make, a few tens of such frequencies may still be of great importance to our understanding of stellar structure and evolution.

In what follows I shall try to indicate what sorts of astrophysical questions one might answer if high-quality oscillations data (such as might be obtained with FRESIP) were available. To this end, I shall first review some of the necessary background physics and jargon. I shall then discuss two kinds of stars: oscillating white dwarfs (chosen because they presently are the best example of what seismological methods can do, and are doing), and stars like the Sun (chosen because their oscillation properties have been well studied theoretically, and because they are observationally intractable from the ground, but are within reach of FRESIP). Last, I shall give a brief listing of the salient observational

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*The National Center for Atmospheric Research is sponsored by the National Science Foundation characteristics of pulsating stars that might reasonably be observed with FRESIP. Most of the following discussion is taken (in rearranged and abridged form) from a review of asteroseismology prepared for Annual Reviews of Astronomy and Astrophysics (Brown & Gilliland 1994). For a more complete treatment of these topics, and for a much more complete reference list, please see that paper.

II. Terminology and Basic Physics

Stars that display pulsations may be described with reasonable accuracy as spheres. For this reason it is possible and convenient to write the pulsation eigenmodes as the product of a function of radius and a spherical harmonic. The spatial and temporal variation of a perturbation to the star's mean state are then

$$\xi_{nlm}(r,\theta,\phi,t) \ = \ \xi_{nl}(r)\ Y_l^m(\theta,\phi)e^{-i\omega_{nlm}t}. \tag{1}$$

Here ξ is any scalar perturbation associated with the mode (*e.g.,* the radial displacement); r, θ, ϕ, t are the radial coordinate, the colatitude, the longitude, and time, respectively. The mode's *radial order* n is usually identified with the number of nodes in the eigenfunction that exist between the center of the star and its surface. Since it deals with the depth structure, n is not accessible to direct observation. The *angular degree* l is the product of the stellar radius R_* and the total horizontal wavenumber of the mode; modes with large values of l display many sign changes across a stellar hemisphere, and hence are usually unobservable on distant stars. The *azimuthal order* m is the projection of l onto the star's equator; it is therefore restricted to be less than or equal to l in absolute value. Note that p-modes may be purely radial ($l = 0$), but that g-modes, since they are driven by buoyancy forces, must involve a variation in the horizontal coordinates, and hence always have $l \geq 1$. The mode frequency ω_{nlm} generally depends on n and l in complicated ways, depending on the restoring forces responsible for the pulsation and on the structure of the star. In particular, there is generally no simple harmonic relation between the frequencies of modes with (for instance) given l and successive values of n. For stars that are truly spherically symmetric, mode frequencies depend only upon n and l, and are independent of m. Any condition that breaks the spherical symmetry (such as rotation about an axis, or the presence of magnetic fields) can lift this frequency degeneracy.

Observations of stellar pulsations usually involve either the photometric intensity or the radial velocity. The displacements of the stellar plasma cause Doppler shifts directly; the accompanying compressions or displacements from equilibrium height also cause temperature changes, resulting in perturbations to the observed intensity. The oscillation parameters that one may observe on stars include not only the mode frequencies, but also amplitudes and linewidths. Frequencies usually carry the most information, because they can be measured accurately and because they can usually be calculated with good accuracy considering only adiabatic effects. Because of the relatively poor current understanding of the physics of mode driving and damping, henceforth I shall concentrate mostly on the information that may be inferred from mode frequencies.

Although mode frequencies depend in complicated ways on the stellar structure, there is a useful limit (that in which $n \gg l$) in which simple asymptotic formulae give useful approximations to the true frequency behavior (Tassoul 1980). For p-modes, one finds

$$\nu_{nl} \ \cong \ \Delta\nu_0\left(n + \frac{l}{2} + \epsilon\right) \ - \ \frac{A\ L^2 - \eta}{(n + l/2 + \epsilon)}, \tag{2}$$

where $\Delta\nu_0$, A, ϵ, and η are parameters that depend on the structure of the star, and $L^2 \equiv l(l+1)$. If the parameters A and η were zero, one would therefore find p-mode frequencies to fall in a regular picket fence pattern with frequency spacing $\Delta\nu_0/2$: modes with odd l would fall exactly halfway between modes with even l, and modes with different n at a given l would always be separated in frequency by multiples of $\Delta\nu_0$. The parameter $\Delta\nu_0$, termed the *large separation*, is simply related to the sound travel time through the center of the star:

$$\Delta\nu_0 = \left(2\int_0^{R_*} \frac{dr}{c}\right)^{-1}, \tag{3}$$

where c is the local sound speed and R_* is the stellar radius. Consideration of the virial theorem (Cox 1980) shows that this travel time is related to the mean density of the star, so that

$$\Delta\nu_0 \cong 135 \left(\frac{M_*}{R_*^3}\right)^{1/2} \mu\text{Hz}, \tag{4}$$

where M_* and R_* are the stellar mass and radius in solar units. Eq. (4) holds exactly for homologous families of stars, but it is obeyed quite closely even for stars that are not homologous, such as stars of different mass along the main sequence (Ulrich 1986). The large separation is thus easily interpreted in terms of the stellar structure, and moreover it is likely to be straightforward to observe, even in noisy stellar oscillation data.

Parameters A and parameters ϵ and η in Eq. (2) have to do with the structure near the center of the star and near the surface, respectively. Modes with different degree l penetrate to different depths within the star. Modes with $l = 0$ have substantial amplitude even at the center; those with higher values of l avoid a region in the stellar core that grows in radius as l increases. This difference in the region sampled by modes with different l leads to the second term on the right-hand side of Eq. (2), removing the frequency degeneracy between modes that differ by (say) -1 in n and +2 in l. This effect is often parameterized in terms of the *small separation*, defined as $\delta_{nl} \equiv \nu_{n+1,l} - \nu_{n,l+2}$. The small separation may be written as an integral analogous to that in Eq. (3) (Däppen *et al.* 1988):

$$\delta_{n,l} = \Delta\nu_0 \frac{(l+1)}{2\pi^2 \nu_{nl}} \int_0^{R*} \frac{dc}{dr}\frac{dr}{r}. \tag{5}$$

The small separation is thus sensitive to sound speed gradients, particularly in the stellar core. Since these gradients change as nuclear burning changes the molecular weight distribution in the star's energy-producing region, the small splitting contains information about the star's evolutionary state.

In the asymptotic limit $n \gg l$, g-mode *periods* (not frequencies) become almost equally spaced:

$$T_{nl} = \frac{T_0[n + l/2 + \delta]}{L}, \tag{6}$$

where T_{nl} is the period of a g-mode, T_0 and δ are parameters that play roles similar to those of $\Delta\nu_0$ and ϵ in Eq. (2), and the other symbols have their previous meanings. The asymptotic period T_0 depends upon an integral of the Brunt-Väisälä frequency N throughout the star (Tassoul 1980):

$$T_0 = 2\pi^2 \left[\int_0^{R_*} \frac{N}{r} dr\right]^{-1}. \tag{7}$$

Another important issue addressable with pulsation data is the frequency splitting of modes with $l > 0$ by the solar rotation (see, *e.g.*, Hansen *et al.* 1977). In the simple case in which angular velocity is independent of latitude, the frequencies of modes within a multiplet are given by

$$\nu_{nlm} = \nu_{nl0} + \frac{m\beta_{nl}}{2\pi} \int_0^{R_*} \Omega(r) K_{nl}(r) dr \ , \tag{8}$$

where β_{nl} is a correction factor of order unity accounting for Coriolis forces, $\Omega(r)$ is the solar angular velocity, and K_{nl} is a unimodular kernel that is roughly proportional to the local energy density in the mode. Thus, the splitting of low-l multiplets (sets of modes with the same n and l but different m) depends somewhat on the angular velocity near the Sun's center, where only eigenmodes with small l have substantial amplitude.

III. Pulsating White Dwarfs

The utility of asteroseismology is perhaps best seen in its applications to white dwarfs. Here, one need not talk about potential rewards or possible conclusions; because of a fortunate confluence of observational and theoretical progress, meaningful results about white dwarfs are available *now*, and more are on the way. Oscillations in white dwarfs are seen as photometric fluctuations with amplitudes that range from roughly 0.3 magnitude down to the limits of detectability; typical periods fall in the range between 100 s and 2000 s. The combination of fairly large amplitudes, short periods, and many excited modes makes the variable WD stars ideal subjects for asteroseismology. Indeed, the successes of WD pulsation studies provide the best current example of asteroseismological methods, and many of the techniques used by the WD community may be viewed as archetypes for the investigation of other kinds of stars.

Strong surface gravity on WD stars discriminates against p-mode pulsations (which involve vertical motions), and favors g-modes (in which the motions are predominantly horizontal). But g-modes may propagate only in regions with stable density stratifications. In white dwarfs, g-modes are therefore confined to the stellar envelope, above the degenerate core. The eigenfunctions may be trapped in an even stronger sense, however, by the rapid jumps in fluid properties that occur at boundaries between different composition layers (Kawaler & Weiss 1990). Although Eq. (6) continues to describe the mean period spacing, the period separation between modes with consecutive values of n shows variations near trapped modes. The detailed variation of period spacing with mode period leads to powerful diagnostics of the near-surface structure.

One of the most straightforward and yet informative applications of WD seismology has been the direct measurement of WD evolutionary timescales, using observations of period changes in WD pulsators. Some pulsating white dwarfs have power spectra that are dominated by one or a few pulsation modes, and in many such cases the frequencies of these modes have proved to be extremely stable. Changes in g-mode periods in evolving white dwarfs may be thought of as resulting from a combination of changes in the temperature and changes in the radius:

$$\frac{\dot{\Pi}}{\Pi} = -a\frac{\dot{T}}{T} + b\frac{\dot{R}}{R} \ , \tag{9}$$

where Π is the period, T and R are the temperature and radius, and a and b are positive constants of order unity (Winget *et al.* 1983). The best characterized case of period change is the prototypical DOV star PG1159-035. As illustrated in Figure 1, this star oscillates in many modes (125 at last count, Winget *et al.* 1991), but a few of these have substantially larger amplitudes than the others. One of these, with a period near 516 s, has been found to have nearly constant amplitude and consistent variation of phase with time over the interval 1979-1989. The rate of period change is quite well determined in this case: $\dot{\Pi} = (-2.49 \pm 0.06) \times 10^{-11}$, corresponding to an evolutionary timescale of about 0.7×10^6 y, with the period decreasing with time. The observed timescale is about what stellar models predict. Unfortunately, however, evolutionary models of DOV stars show that the periods of typical g-modes should *increase* with time, as cooling dominates the effects of global contraction in Eq. (9) (Kawaler *et al.* 1986). The explanation for this contradiction is probably that the 516 s mode is not typical; it is a trapped mode, for which changes in the stratification dominate effects of changing overall structure. Kawaler (1993) finds that detailed models of PG1159-035 give trapped modes with very nearly the observed period; these modes display negative values of $\dot{\Pi}$, although no model gives negative period changes that are as large in magnitude as that observed.

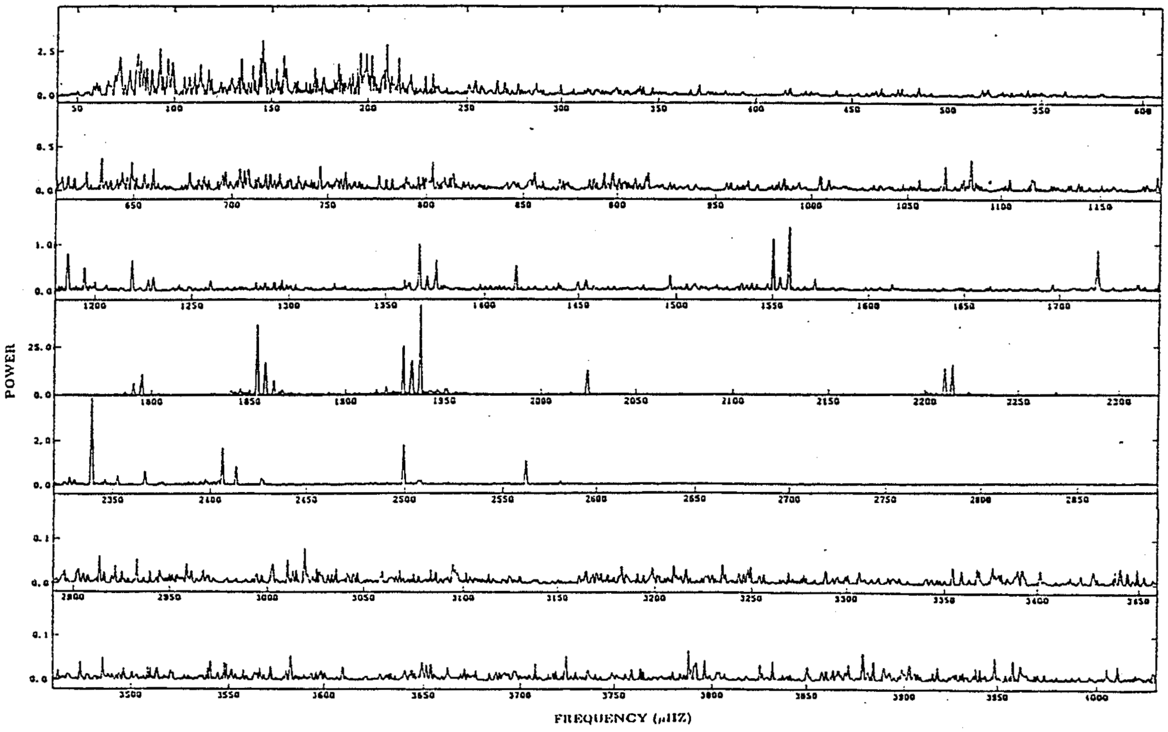

Fig. 1. Power spectrum of the intensity pulsations of PG1159-035, as observed by the Whole Earth Telescope. Note the vertical scale differs from panel to panel, to accommodate the large dynamic range. From Winget *et al.* (1991).

Interpretation of the power spectrum shown in Figure 1 has yielded a tremendous amount of information concerning PG1159-035 (see Winget *et al.* 1991, and references therein). Among the most firmly established and interesting results are the following: (1) Virtually all of the peaks seen in the power spectrum may be identified as members either of triplets (with $l = 1$) or quintuplets (with $l = 2$). Conclusive evidence for the l identification is provided by the ratio of period spacings for the two kinds of multiplets. Models show that this ratio should be within a few percent of its asymptotic value of $\sqrt{3} \cong 1.73$, while the observed ratio is 1.72. (2) The source of the frequency splitting within multiplets is apparently rotation of the star. This identification is consistent with the presence of $2l+1$ components in each multiplet (as in Eq. 8), and moreover the observed frequency splittings for triplets and quintuplets are consistent with the calculated values of β_{nl} from Eq. (8). The inferred rotation period for the star (assuming uniform rotation) is 1.38 ± 0.01 days. (3) The presence of a significant global magnetic field would induce a component of the frequency splitting proportional to m^2. No such symmetric component is observed; the observed limit on its magnitude implies a maximum global field strength of about 6000 G. (4) The mean period spacing between multiplets is 21.5 s for $l = 1$ and 12.7 s for $l = 2$. For stars like PG1159-035, these mean period spacings depend mainly on the stellar mass, with little dependence on other parameters. The observed period spacings thus allow an accurate estimate of the stellar mass; in this case the seismic mass is $0.59 \pm 0.01\ M_\odot$ (Kawaler 1993). (5) Departures from uniform period spacings can be interpreted in terms of the chemical stratification of the WD envelope. The fairly large (±10%) observed variations from the mean spacing can be modeled surprisingly well using either evolutionary models starting from post-AGB progenitors, or using less restrictive structural models, as shown in Figure 5, (Kawaler 1993). The model-fitting process gives what appear to be secure values (listed in the figure) for the mass, the effective temperature, the mass of the helium-enriched surface layer, and the surface helium abundance.

IV. Pulsations in Sun-Like Stars

The best-studied and understood stellar pulsator is of course the Sun. There is no cause to believe that the Sun is an extraordinary star of its type, so it is reasonable to expect that other stars like the Sun pulsate in much the same way the Sun does. Unfortunately, the amplitudes of the solar p-modes are so small that detecting them on distant stars is a challenge; in order to justify the efforts required to do so, it is prudent to examine in considerable detail the kinds of information that one would get, should p-mode frequencies of other stars become available.

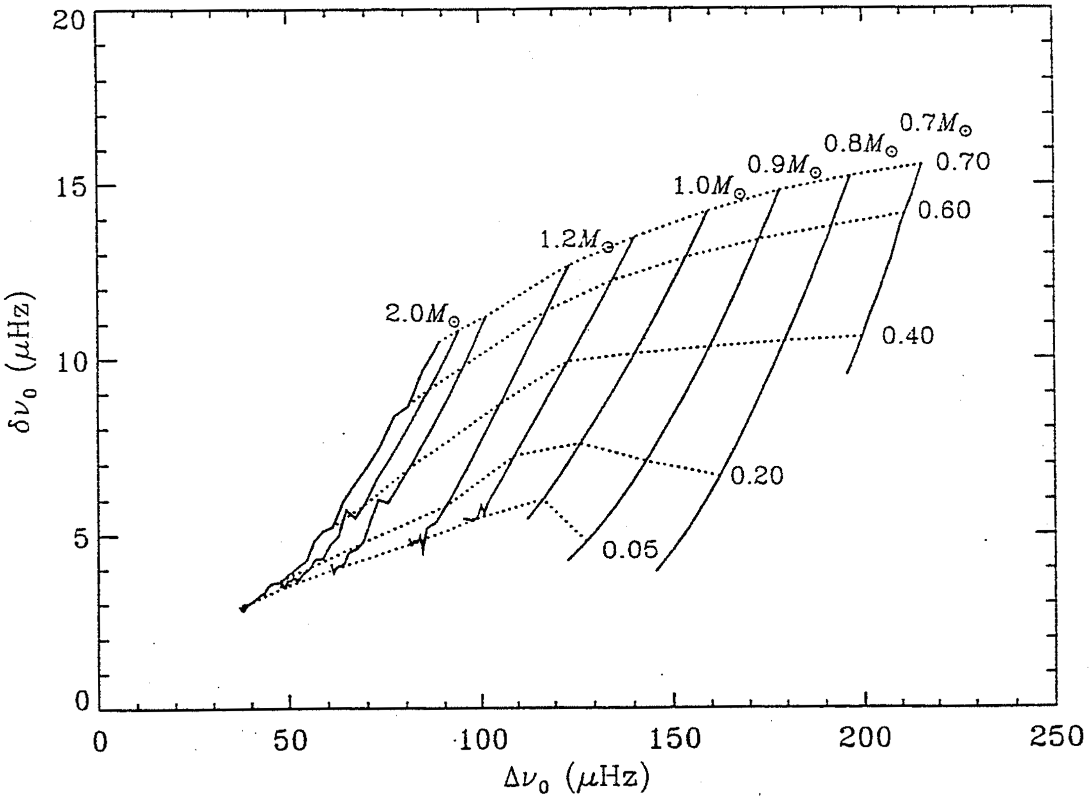

Fig. 2. The "asteroseismic H-R diagram" of Christensen-Dalsgaard (1988), showing the variation in large ($\Delta\nu_0$) and small ($\delta\nu_0$) frequency separation with stellar mass and age. Mass is constant along solid lines; age (parameterized by the central hydrogen abundance) is constant along dotted lines.

The first efforts to estimate the information content of oscillation frequencies for Sun-like stars were made by Ulrich (1986, 1988) and by Christensen-Dalsgaard (1988). These authors computed the sensitivity of the frequency separations $\Delta\nu_0$ and δ_{nl} to changes in the stellar mass M and age τ; Ulrich (1986) also considered changes in the initial composition parameters Y (the helium abundance), Z (the heavy element abundance), and in the mixing length ratio α. They concluded that if the composition were known, then measurement of the two frequency separations would allow the stellar mass and age to be estimated with useful precision. These results are summarized in the so-called "asteroseismic H-R diagram," shown in Figure 2. If one assumes that individual mode frequencies may be measured with precision comparable to the mode linewidth (unknown for other stars, but typically 1 μHz for the Sun), then Figure 2 suggests that frequency separations could be used to determine stellar masses to within a few percent, and ages to within perhaps 5% of the main-sequence lifetime.

Brown *et al.* (1994) performed a more complete treatment of the problem of estimating model parameters from p-mode frequencies. Estimates of the age, mixing length, and mass of field stars can be substantially improved by the addition of oscillation frequencies. Indeed, without the frequency data, parameters such as the age are essentially unconstrained, and must be estimated from more general considerations, such as the age of the galaxy. The relative improvement in errors is greatest for distant stars, for which astrometric data are relatively unreliable. The lowest absolute errors, however, occur for nearby stars with high-quality astrometry. It develops that oscillation frequency data is usually unhelpful in constraining the heavy element abundance Z. In the best field star cases, one should be able to reach errors in mass and mixing length of about 3%, and in helium abundance and age of about 12%. Errors of this size would be interesting from the point of view of galactic evolution if they could be obtained for a good sample of stars near the Sun. They are not, however, small enough to allow tests of the physics of stellar structure theory.

A more interesting situation occurs if mode frequencies can be obtained for both stars in a well-observed visual binary (α Cen, for example). In such a case the two stars may be assumed to have the same age, distance, and initial composition, so that the number of parameters required to describe the system is less than twice that for a single star. Moreover, some new observables (the orbital data) provide fundamentally new sorts of information. One result is that parameter errors become smaller for binaries than for field stars. A more important difference is that, with many more observables than model parameters, one may search for inconsistencies between the observations and the best-fit model. If significant inconsistencies are found, then significant errors must exist in the model of the star system. In this way, it may be possible to detect errors in the physics underlying the calculation of stellar structure. For example, observed properties of a binary system (chosen to be similar to the α Cen system) were constructed using one set of opacity tables, but were fit to a model based on different (but plausible) opacities. Since the "true" and assumed models of the system employed different physics, no combination of model parameters could match the constructed observations exactly. The residuals between the "true" observations and those implied by a best fit to the model using OPAL opacities are generally large enough to be detected in spite of observational errors, and the pattern of discrepancies provides clues to the nature of the error in the assumed model. Not all modifications of the input physics result in changes that are as large as those in this example, and the degree to which different physical effects may produce similar sets of residuals is not yet known. Nonetheless, it seems reasonable that oscillation frequencies, if available, would not only allow measurement of the structural parameters of stars, but would also place constraints on at least some aspects of stellar evolution theory.

V. Expected Characteristics of the Pulsations

Having established the utility of pulsation information, one must next ask what the observable properties of stars accessible to FRESIP might be. In what follows, I shall first describe expectations for Sun-like stars, extrapolating as needed from the Sun itself to other, similar stars. Then I shall summarize in tabular form the key observational properties of all of the multimode pulsators that might be observed by FRESIP.

Figure 3 shows the power spectrum of solar p-modes as measured with the IPHIR full-disk photometer while *en route* to Mars on the Soviet Phobos spacecraft (Toutain & Frölich 1992). The IPHIR instrument measured the brightness in several colors, integrated over the visible disk of the Sun, using silicon diode photometers. Except for their low noise level, these observations are thus closely analogous to normal photometric observations of stars. Figure 3 illustrates several important aspects of the solar p-modes. First, the mode frequencies are very well defined, with typical quality factors Q of several thousand. Second, the mode amplitudes are large only within a restricted frequency range, between roughly 2500 and 4000 μHz. Within that range, the low-degree modes to which IPHIR is sensitive are indeed almost evenly spaced in frequency, and in spite of the compressed frequency scale of this figure, many close pairs of modes (corresponding to $l = 0, 2$ or to $l = 1, 3$) may be seen. The separation between pairs of modes turns out to be roughly 68 μHz $= \Delta\nu_0/2$; the separation between modes making up a given $l = 0, 2$ pair is about 9 μHz. The amplitudes of the pulsations are quite small: the largest peaks near 3000 μHz have power corresponding to amplitudes $\delta I/I$ of only about 3×10^{-6}.

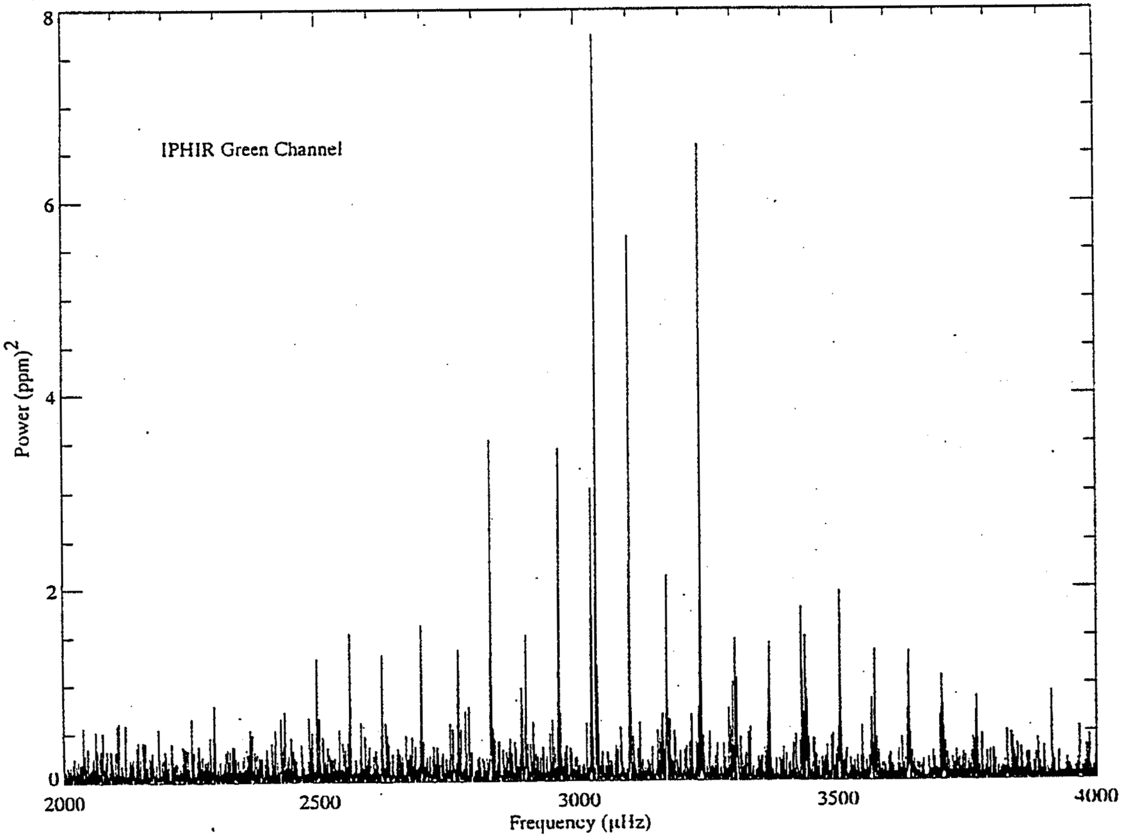

Fig. 3. Power spectrum of one month of disk-integrated solar intensity measured by the green channel of the IPHIR experiment. From data provided by C. Frölich (see Toutain & Frölich 1992).

It is fairly clear that the source of energy for the Sun's p-modes is acoustic noise generated by high-speed convective motions within a few scale heights of the solar surface (Cox *et al.* 1991). This implies that all stars with vigorous surface convection zones (which is to say, all stars with spectral types later than roughly F5) should support p-modes that are more or less similar to those observed in the Sun. Christensen-Dalsgaard and Frandsen (1983) estimated oscillation amplitudes as a function of T_{eff} and surface gravity, assuming radiative damping as the dominant energy sink and a now-obsolete form of the theory of convective mode excitation. The results suggest a weak dependence of mode surface amplitude on surface gravity (*cf.* Eq. 9). Their results may be parameterized as

$$\frac{v_*}{v_\odot} = 2\left[\left(\frac{g_*}{g_\odot}\right)^{0.6} + \left(\frac{g_*}{g_\odot}\right)^{4.5}\right]^{-1} \tag{10}$$

where v_* is the typical rms velocity amplitude of the largest stellar mode, $v_\odot$ is the same quantity for the Sun, and g_* and $g_\odot$ are the stellar and solar surface gravities, respectively. This estimate is very uncertain, and of course says nothing about the likely lifetimes of p-modes on other stars.

A rough estimate can be made of the frequency range within which oscillations would be seen on distant stars. In the WKB approximation, the reflection of sound waves as they propagate upward through a stellar envelope is governed by the behavior of the *acoustic cutoff frequency*, ω_{ac}. Waves propagate upward until the local value of ω_{ac} becomes greater than the wave frequency, and then they reflect. In the simplest (isothermal layer) approximation, which is adequate for our purposes, one may write

$$\omega_{ac} = \frac{c}{2H} \propto gT^{-1/2} \ , \tag{11}$$

where c is the local sound speed, H is the pressure scale height, g is the gravitational acceleration, and T is the temperature. In stellar atmospheres, ω_{ac} reaches a maximum, ω_{ac0}, in the photosphere, where the temperature is minimum. Waves with frequencies above ω_{ac0} never reflect, but rather continue propagating into the tenuous outer parts of the stellar atmosphere. As a result, p-modes with frequencies above ω_{ac0} are not expected to attain significant amplitudes. On the other hand, modes with frequencies much smaller than ω_{ac0} reflect deep in the stellar envelope. This reduces the surface amplitude for a given mode energy, and moreover reduces the coupling between the mode and the near-surface convective driving source. These considerations suggest that maximum p-mode amplitudes should be found at frequencies that are a modest fraction (roughly 0.6, in the Sun) of ω_{ac0}. From Eq. (11), it follows that the expected frequency of maximum p-mode amplitude should scale as $gT_{\mathrm{eff}}^{-1/2}$. If one adopts the scaling appropriate to the Sun, this implies cyclic frequencies ranging from about 1 mHz (for F-type subgiants) to about 10 mHz (for M dwarfs). The foregoing suggests that the most attractive targets for stellar oscillation searches should be stars that have lower surface gravity and are more luminous than the Sun, since such stars should have larger amplitudes (*cf.* Eq. 10) and should pulsate with longer periods (simplifying many observational problems).

Where stars of non-solar type are concerned, it is risky to generalize about oscillation properties because of the wide range of physical conditions involved, and because of our poor understanding of many of the important processes. Table I nevertheless attempts to do just that. For each of the categories of star that may yield asteroseismological information (including δ Scuti and roAp stars, which I have not mentioned here – see Brown & Gilliland 1994 and Kurtz 1990 for a discussion), the table lists: (1) FRESIP m_V, an estimate (guess!) of the visual magnitude of the brightest object of this class to fall within the FRESIP field of view. The arguments leading to this guess are purely statistical; I have done no searches. (2) ν_{max} (μHz), a typical pulsation frequency. (3) $\Delta\nu_0$, and (4) $\delta\nu_0$, typical large and small frequency separations (whatever these may mean, given the context). (5) $(\delta I/I)_{rms}$, a typical photometric amplitude for the largest modes. The feasibility of observing (either from the ground or from space) pulsations such as those described in the table are discussed by Gilliland (these proceedings).

TABLE I.

Star Type	FRESIP m_V	ν_{max}	$\Delta\nu_0$	$\delta\nu_0$	$(\delta I/I)_{rms}$
White Dwarf	14 (?)	2000	100	1	0.03
δ Scuti	8	200	–	–	0.01
roAp	10	3000	100	10	3×10^{-3}
Sun-Like	8	3000	100	10	3×10^{-6}

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Asteroseismology – Ground Based Efforts and the Need for Space Observations

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Abstract. Detection of the oscillations expected to be present on solar-like stars is very difficult. Photometric observations from the ground suffer from two problems: 1) an atmospheric scintillation noise that drops only slowly with telescope aperture size, and 2) mode frequency spacings that require nearly continuous observations over at least several days for resolution. I will review the very limited possibilities for asteroseismology of solar-like stars from ground-based photometric observations. FRESIP could provide an excellent opportunity for pursuing asteroseismology observations of a far richer nature than can be contemplated from the ground.

1. Introduction

The companion paper in this volume by Tim Brown (1993) will have introduced the science of asteroseismology. Through the detection and detailed quantification of stellar oscillations on a large number of different stars we should be able to open a fundamentally new and important chapter in stellar astrophysics. The information that may be gained from asteroseismology should allow a useful confrontation with stellar structure and evolution theory.

In this paper I will concentrate on reviewing the results from a recent large scale photometry campaign (Gilliland, *et al.* 1993) directed toward detection of oscillations on subgiant stars in M67. I will emphasize that although the study of oscillations on solar-like stars using ground based photometry is not hopeless, it is very difficult and will remain of limited utility. Since the observational requirements of the FRESIP project so nearly match those for asteroseismology, the latter is an ideal candidate for auxiliary science with FRESIP. In §2 I will outline the basic observational requirements for detection of stellar oscillations. Section 3 will be devoted to a discussion of the largest ground-based photometry campaign to date. The capabilities and limitations of a possible future ground-based observing campaign making use of 10-12 of the worlds largest telescopes for a full week will be the topic of §4. (Parts of §3 and 4 have been adopted from

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[1] Guest Observer, Kitt Peak National Observatory, National Optical Astronomical Observatories, Operated by AURA, Inc., under contract with the National Science Foundation.

[2] Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Aeronautics and Space Administration.

a previous conference contribution: Gilliland 1993.) The capabilities of FRESIP to support asteroseismology will be discussed in §5. A summary will be provided that includes a note that planetary detection (via photometry) is probably even more difficult to pursue from the ground than is asteroseismology.

2. Observational Requirements for Detection

Photometric observations acquired through the Earth's atmosphere have a (probably irreducible) noise component from atmospheric scintillation (e.g., see Young 1967; 1974). The atmospheric scintillation has been parameterized by Young as:

$$\delta I/I = 0.09D^{-2/3}X^{1.75}\exp(-h/h_o)/(2t_{int})^{1/2} \tag{1}$$

where I is the intensity, D is the telescope aperture diameter in cm, X is the airmass, h is the telescope altitude relative to the atmospheric scale height h_o (~8000m) and the integration time in seconds is t_{int}. Unfortunately this equation exhibits only a weak fall off with telescope aperture size and a fairly strong increase with airmass. Even with the largest telescopes at high altitude, atmospheric scintillation strongly limits the photometric precisions that could otherwise be obtained.

On a 4-m telescope Eq. (1) predicts a noise floor of ~215 μmag per minute of observation when averaged over an 8 hour window. Stars brighter than $m_B \sim 12$ will have Poisson errors less than this when observed with efficient detectors and a wide-band photometric filter. Thus in simple terms of limiting noise all stars with $m_B \leq 12$ are equal for 4-m class telescopes. (This assumes that other sources of noise such as atmospheric transparency variations can be controlled. In practice this further restricts candidate stars to fields with good ensembles within a small field of view.)

The number of observations required to detect a coherent oscillation of amplitude, A, given a time series of precision (rms), ϵ, may be written (Scargle 1982):

$$N_{obs} = 16(\epsilon/A)^2 \tag{2}$$

where we have assumed a significance level of 4-σ is desired. Evaluation of Eq. (2) for the Sun observed as a star with 4-m telescopes quickly points out the fundamental problem inherent in ground-based photometry to detect stellar oscillations: the signal is small compared to the noise. Specifically we might assume that a 4-m telescope (or network of such) could deliver 300 μmag precision per minute if other noise sources end up equaling scintillation. With the solar amplitude of about 3 μmag Eq. (2) requires 160,000 observations, or 111 full observing days, for detection. To obtain 111 full observing days given average weather conditions would require simultaneous allocation of time for the full period on six telescopes well separated from each other. Even with 10-m telescopes at 4,000m altitude it would take 35 (full) days to (just marginally in a quantitatively useful sense) detect oscillations on a strict solar analogue. Clearly ground-based photometry does not seem useful in these cases.

For ground-based photometry to have a decent chance of success stars with more favorable amplitudes must be selected. Christensen-Dalsgaard and Frandsen (1983) have predicted based on theory that F-G subgiants should have amplitudes of up to about five times solar. At this more favorable amplitude 4-m class telescopes might allow detection in 5 days (again this assumes full 24 hour days), while ideal 10-m class telescopes might do the same in less than two days.

Although five full days, which in practice requires a collaboration involving six sites all assigned for the full time, on 4-m class telescopes is a major effort, it is not beyond the realm of feasibility. Gilliland and Brown (1992) provided detailed predictions of what such a 4-m project might accomplish and selected a nearly ideal (from both observational and theoretical constraints) ensemble of 11 stars in the old open cluster M67.

Before moving to a discussion of the 4-m network observing campaign I need to point out two additional items related to oscillation detection. First is the obvious condition that the sampling interval must be shorter than half the oscillation period. For the level of detail required in this paper integration periods of about one minute are required. This is the only obvious change to plans for FRESIP to support asteroseismology: for at least a subset of the brighter stars an observing cadence of one minute should be adopted. The second item to consider is how long the observing runs must be to return useful information. For the stars of M67 (F-G subgiants) the smallest mode frequency separations of $\sim$3 μHz would require a five day time base to safely resolve. In general much longer time bases would be preferred in order to support higher precision oscillation frequency determinations.

An additional consideration is what generates the network requirement. The principle feature characterizing multi-mode oscillations is the mode separations in frequency space. This is of both theoretical interest and observational convenience given that the repeated structures in a power spectrum can be exploited (via power spectra of power spectra techniques) to show the presence of weak signals, none of which could be believed individually. For the Sun this mode separation is 68 μHz; this can be resolved with observations spanning $\sim$1/68 μHz = 4.5 hours. Stars of still roughly solar type, *e.g.* the upper main sequence and subgiants of M67 selected to have expected oscillation amplitudes of 3 to 5 times solar have mode separations of 20 to 40 μHz. At 40 μHz the observation window required for frequency resolution is 7 hours, at 20 μHz the required window is 14 hours. Observations obtained from a single site with nightly eight hour observing windows will marginally support detection of splittings at 40 μHz, but do not carry any information at 20 μHz, at least for the straight forward power spectrum of power spectrum analysis technique. Nightly eight-hour windows with 16 hour gaps carry this autocorrelation type of information for frequencies between 1/8 hours $\sim$35 μHz out to the Nyquist frequency of the individual observations (8.3 mHz if a one minute cadence is assumed). Frequencies from 1/16 hours $\sim$17 μHz (time from end of one window to start of the next) down to the inverse of the total time base may also be resolved. *But the frequency desert domain of 17 to 35 μHz is not sampled by nightly observations with eight-hour windows no matter how many nights from a single site are strung together.* This is not to claim that no information on modes separated by 17 to 35 μHz is contained in data acquired with nightly eight-hour windows. δ Scuti stars (see, *e.g.,* Gilliland and Brown 1992b) often show individual modes with well determined frequency differences between 17 and 35 μHz, but this is for high signal-to-noise data analyzed via direct sinusoidal fits. For the low signal-to-noise data certain to hold for solar-like oscillation experiments, the observations must be structured so as to remove the frequency desert associated with gapped data. In a formal sense the frequency gap for power spectra of power spectra disappears for 12 hour and greater windows. In practice the relative sensitivity for splitting in the general frequency domain of 20-40 μHz improves rapidly for windows of 12 to 18 hours with gains still to be made through elimination of all gaps.

Stars with mode separations favorable to detection with observations feasible from single sites (*e.g.* close solar analogues) have such small predicted amplitudes that even a 10-m telescope would not yield good enough precision. Stars with more favorable amplitude predictions (*e.g.* subgiants) have mode separations that require nearly continuous network campaigns. For the detection of weak oscillations characterized by frequency separations of 20-40 μHz a nearly complete longitude distributed network is a practical necessity. Lunar based observations could be ideal for the study of solar-like oscillations. Single nightly transits could extend to over 12 days allowing for frequency resolution of less than 1 μHz which is a good match to desired precisions for asteroseismology of solar-type stars.

3. Results From 4-m Network Campaign (Jan '92)

Given the need for several 4-m class telescopes observing in concert for about a one-week period, much effort was devoted to background studies and presentation of fundamentals. Gilliland and Brown (1992a) describe the work done to justify devoting some thirty nights of allocated 4-m time to this single observational project. Previous experiments on 1-m and 2-m class telescopes had shown that CCD ensemble photometry could deliver atmospheric scintillation plus Poisson statistics limited precision for relative time-series photometry of a stellar ensemble. A minor extrapolation from empirically obtained and theoretically understood results showed that 4-m observations should allow precisions of $\sim$300 μmag for one minute integrations for stars of $m_B \leq 13.0$ as averaged over eight hour observing windows.

The 4-m network that was realized for January 1992 consisted of seven sites (two were only 2.5-m class telescopes and therefore would yield lower precision per unit time) for a total of 34 nights. With reasonable assumptions about weather losses (assume $\sim$60% clear) such a campaign was predicted to support detection levels corresponding to 16 μmag (best cases), or about four times larger amplitude than the Sun.

The selection of a stellar ensemble to observe was driven by observational constraints; in particular the best possible match to the (Cassegrain mounted 512×512 T5HA CCD covering a field of 95 arcsec) setup at Kitt Peak was sought. The dipper asterism field of M67 contains eleven stars of 12th and 13th magnitude in B within an 80 arcsec square and has few fainter background contamination stars. Also important is that the eleven stars are mutually well separated (12" nearest neighbor) and have similar colors. Based on detailed searches this is believed to be the best field in the sky from purely observational constraints. From a theoretical perspective this is also an ideal field. All of the ensemble stars are high probability members of the cluster and M67 is one of the most thoroughly observed clusters – a necessary condition to support full utility of any success at quantifying oscillation frequencies for some of the stars.

The observing campaign from 12-18 January 1992 resulted in a total of 156 hours of time series observations on the M67 ensemble over 22 separate telescope nights. The time-weighted mean aperture size contributing to the time series was 4.04 m. Sites returning useful data were: the 4-m at Kitt Peak, the 5-m at Palomar, the 3.6-m CFHT, the 3.9-m Anglo Australian Telescope, the 3.5-m at Calar Alto in Spain, and the 2.5-m Nordic Optical Telescope in the Canaries. The longitude distribution was sufficient to provide time-series coverage 64% of the time over a six-day period. During good observing conditions precisions of ~300 μmag each minute were reached, as expected.

Discussion of two special problems, one recognized before and the other after data was obtained, may be used to illustrate the special care required to reach the high precisions needed for this project.

Before the run it was recognized that differences of equipment and setup across the sites demanded thorough development of observing plans. At Kitt Peak the CCD had 0.18" (27 μ) pixels with deep ($5 \times 10^5 e^-$) linear wells. The brightest star would reach an ideal level of about half saturation at peak intensity for nominal 1.5" seeing and a 60 second integration time. At CFHT the CCD had 0.2" (15 μ) pixels with a shallow well depth – not uncommon 0.6" CFHT seeing would push the saturation limit with exposure times of only ~1 second. With a 14 second readout overhead a disastrous duty cycle of ~7% would result, *i.e.,* most of the time that should be spent averaging down atmospheric scintillation fluctuations and collecting photons to minimize the Poisson noise would actually be spent cycling the CCD. Under such conditions the data collected from CFHT (nominally expected to be the best site based on projections for atmospheric scintillation) would not contribute in a meaningful way. An obvious solution was to defocus the images at CFHT, allow much longer integrations and thus restore a good duty cycle. But too much defocus would blend the stellar images together and compromise the intensity extraction estimates. In order to use the correct defocus we generated a predictive error budget for each site as a function of any selectable (CCD options, f-ratio, etc.), or adjustable (defocus, integration time) options and solved for the set providing the smallest time series errors. Part and parcel of this process was empirical testing on a setup field before M67 could be observed at the beginning of nights.

After the fact a subtle nonlinearity at low intensity was recognized in the CCD used on the Palomar 5-m. The nonlinearity was such that for an input level of 1000 detected photons the signal level was ~10% lower (in a relative sense) than for an input signal 10 times larger. At lower intensity levels the effect was relatively larger, at levels above 5000 photons linearity was maintained. Due to fluctuations in low-intensity components of the images (from sky and seeing) this subtle low-intensity nonlinearity resulted in a much increased error budget (factor of two) for the Palomar time series. Once recognized it was possible to correct for this in the CCD reduction phase and reach final precision levels as expected.

A detailed analysis of the error budget showed that under good conditions the time series noise level varied in a way which followed the predictions for atmospheric scintillation plus Poisson noise limited data. As an example, the 4th brightest star in the ensemble showed a time series standard deviation (data from one night) of 252 ppm over the three hours at minimum airmass (77 second integrations), compared to a direct simulation of 238 ppm based on atmospheric scintillation, Poisson object noise and sky plus CCD readout contributions added in quadrature. At the three hours of highest airmass the observed standard deviation was 362 ppm (85 second integrations) versus a modeled value of 387 ppm (the latter suggests atmospheric scintillation probably increased more slowly than airmass to the 1.75 power assumed). In times of poor and variable seeing, or with variable transmission, the errors would exceed the limiting levels, but degradation with poor conditions was very modest. CCD ensemble photometry allows atmospheric scintillation plus Poisson statistics limits to be reached on 4-m telescopes and does so in a robust way that continues to provide excellent results even when conditions are far from photometric in quality.

Although the network campaign provided an immense amount of data (~8000 data points on 11 stars each with mean noise levels of about 300 to 500 ppm over the full time series), the search for oscillations is difficult. At best we might expect a S/N per data point of about 0.1; a time series plot will look like pure noise even if such a coherent signal is present. Through power spectra analyses the evidence for such signals can be brought out.

Solar observations show that many modes are simultaneously excited. The independent modes tend to be evenly spaced in the frequency domain (this is theoretically understood as individual modes differing by single steps of a high radial overtone quantum number) creating a picket fence effect (*e.g.* see Toutain and Fröhlich 1992) in power spectra. Searching for evenly spaced modes in the power spectra can provide another handle on detecting oscillations and this spacing is the theoretically interesting quantification (to lowest order) of the oscillations.

The full process of CCD data reduction, intensity extraction, massaging of time-series data, and power spectrum analysis is quite complicated and not amenable to providing direct 'error bars' on results. In all analyses we rely heavily on simulations to know: If a signal of a certain amplitude were present would we detect it? If no signal is present will we reach a null conclusion?

The following conclusions may be drawn from detailed analysis of the real data in comparison with hundreds of realistic simulations:

1. In no cases are stellar oscillations detected *unambiguously.*

   A working definition of unambiguous: no reasonable scientist would doubt the basic detection. The signal would be obvious when analyzed in an appropriate way and this level of confidence is required to be of utility in challenging theory.

2. In the two stars with the lowest noise, multi-mode oscillations with peak amplitudes of 25 and 28 ppm respectively would have been unambiguously detected.

   This result involves a substantial number of reasonable assumptions regarding the simulations used for 'calibration.' With this caveat in mind firm upper limits of 25 and 28 ppm (6-7 times solar) may be placed on oscillations in the two best cases. This result is just at the margin of being interesting to theorists, *i.e.,* it seems unlikely that amplitudes are larger than suggested by simple theory (Christensen-Dalsgaard and Frandsen 1983), but the upper limits are not in conflict with expectations.

3. About half of the ensemble stars show evidence of oscillations with a distinct tendency for the inferred frequencies to be in good agreement with theory. The suggested amplitude of peak oscillations for these cases is about 20 ppm.

   Unfortunately, detailed Monte Carlo style simulations show that similarly suggestive evidence would appear about 5% of the time given time series of pure noise analyzed in the same way. The significance of positive detections is therefore about 2σ.

4. Advanced Network Campaign Possibilities

The 4-m network campaign realized in January 1992 was sufficient to reach precision levels of interest for detecting oscillations on the stars in question. Oscillations may have been seen, but if so only at significance levels too low to support challenges to theory. Given the cost in terms of telescope time and the organizational effort of setting up such a campaign, a mere repeat is probably not justified.

It seems likely based on current theory that 100% improvement in the observational sensitivity would support unambiguous success for most of the M67 ensemble stars. What changes to the realized network would be required to yield a factor of two gain for the 'best' star in the M67 ensemble? What changes would be required to yield an across the board factor of two gain in sensitivity?

The 4-m network campaign included telescopes at Kitt Peak, Palomar, Mauna Kea, Australia, Spain, and the Canary Islands. The latter two sites contributed generally low importance data (the site in Spain contributed only part of one night, the site in the Canaries was 'only' a 2.5-m telescope). Although observations had a 64% filling factor over six days, or ~15 hour windows on average, the data from the Eastern flank was relatively weak compared to that from the American southwest. The actual network yielded good data on 20 full telescope nights. The star showing the best evidence for oscillations had a predicted (and at 2σ detected) frequency separation of adjacent modes of ~19 μHz. Simulations show that the oscillation characteristics expected for this star are particularly sensitive to the network data distribution. Adding five (summer) nights from the CTIO 4-m in Chile, three nights from the 4.2-m WHT in the Canaries, and two nights from the Russian 6-m improved sensitivity for mode separations at 19 μHz by a full 100%! From simple signal-to-noise considerations adding 10 nights to the already existing 20 nights would result in a $(3/2)^{1/2}$, or about 22% gain. But by adding the additional time at ideal longitudes the gain is a full 100%, a doubling of sensitivity for only a 50% augmentation. For ensemble stars with expected frequency separations of about 40 μHz the gain would be about 30% with most of the improvement following from simple $N^{1/2}$ considerations.

The ensemble stars with expected mode separations of ~35-40 μHz require primarily a brute force addition of data for improved sensitivity. Adding in seven nights each from the Keck 10-m and the MMT 6.5-m upgraded telescopes would allow a factor of two sensitivity increase for these stars.

A network campaign consisting of the six sites yielding data in January 1992, plus the CTIO 4-m, WHT 4.2-m, Russian 6-m, Keck 10-m and MMT 6.5-m – all with seven night allocations – would better than double the sensitivity gains for all the M67 ensemble stars. With such a campaign unambiguous success capable of supporting a real challenge to stellar structure and evolution theory would be expected.

Successfully justifying a simultaneous one-week allocation on most of the world's largest telescopes would be no mean feat. The science to be derived from observations of a coeval M67 population might well justify such an observing campaign; any results would likely be complementary to what would follow from early space observations. However, in a wider scope the opportunities provided by space observations would far surpass what can be contemplated from the ground.

5. What Could be Done With FRESIP?

The prospects of pursuing photometric detection of stellar oscillations from space is excellent. Even a modest 1-m class telescope in space can easily outperform networks of much larger telescopes operating from the ground. The fundamental noise limitation from atmospheric scintillation does not exist for space observations. Placed in a suitable orbit a space observatory may obtain continuous monitoring for very long periods of time – conditions that are ideal for asteroseismology. Given the existing plans for FRESIP, modifications to allow stellar oscillation detection could be included with little additional cost or complexity.

The FRESIP project is imagined to be a 1.0 to 1.5-m very wide-field ($\sim$100 square degrees) telescope with several large format CCDs covering the focal plane. The images for some 8,000 program targets would be defocused to allow excellent signal-to-noise at very high count rates – ideal for asteroseismology. The CCDs would be read out at a rapid (few second) cadence with on-board processing providing summed intensities once per hour for previously identified targets to support planetary identification via periodic transit signals. This is a demanding, but potentially very powerful approach, that requires continuous viewing of the same field for at least three years – again ideal for asteroseismology. To provide excellent results for stellar oscillations would simply require that the signals for a subset of the stars be compiled on one minute intervals. Although elimination of noise from cosmic rays will be a challenge for on-board processing, it should be possible to maintain precisions that are close to the Poisson limit. Assuming CCDs with high efficiency, a 3000 Å wide filter and a 1-m telescope, then the count rate for FRESIP on an $m_B = 10.0$ star would be order 10^8 per minute for a Poisson noise of 100 ppm (ppm are equivalent to μmag used earlier to within 8%). At this precision (near the bright limit due to detector saturation) the solar amplitude could be marginally detected in about 12 days. Quantitatively robust frequency determinations would follow with data acquired on 10 times the temporal period (factor of three signal-to-noise gain) required for a simple marginal detection. Oscillation detection on early K dwarfs would require measurement of amplitudes a factor of five lower (Christensen-Dalsgaard and Frandsen 1983) than solar and thus require 25 times as long for a basic detection. Following about 100 stars each of F, G, and K spectral types would allow invaluable statistics to be built up for the nature of p-modes on other stars (currently the Sun is the only solar-like star with a secure and quantitatively useful detection). The continuous monitoring would provide a perfect window function that is essential for robust interpretation of the data, but is so hard to come by with ground-based observations. The long time base would support both very precise frequency determinations and allow testing for frequency changes as may arise from stellar activity cycles. The asteroseismology data set that could result from FRESIP would provide fundamentally important information for the understanding of p-mode driving and for stellar structure and evolution theory.

6. Summary

I have argued that photometric detection of stellar oscillations on solar-like stars should be possible from the ground. However, a successful ground-based experiment is likely to require a heroic effort that cannot be repeated often and that will not extend over a sufficiently long time base to address many issues of interest. A network campaign conducted in January 1992 with 30 nights (average of 5 each at 6 sites) allocated was not sufficient to yield unambiguous results even on stars with favorably high predicted amplitudes. The 4-m campaign gave results a factor of three more sensitive than in any previous experiment. Further substantial gains will come only at a high cost in terms of telescope time. A network consisting of 10-12 of the worlds largest telescopes as should exist in 1997, all collaborating for 7 nights (i.e., 70-84 allocated nights at a mean aperture size over 5-m), would provide a further factor of two sensitivity gain. (The latter would be quite significant, since such would allow a prediction of clear success in detecting oscillations on several interesting stars.)

For completeness I should point out that Doppler measurements through high resolution spectroscopy is an additional technique applied to asteroseismology observations. Although the prospects are good for this technique to succeed in the near future, there are no unambiguous detections yet despite many efforts. This technique is most applicable to very bright stars. The need for network observations and long time bases will also limit results relying on spectroscopy.

Having spent several years pursuing very demanding ground-based observations directed toward stellar oscillation detection, I would like to comment on the prospects of conducting a FRESIP experiment from the ground. I would consider the potential for success at this to be even bleaker than for asteroseismology via photometry. The stellar oscillations have periods very short compared to nightly observing windows, we can therefore simply filter out or ignore any low frequency noise. The planetary detection experiment will be seeking signals with a characteristic time scale comparable to nightly observing windows as forced by the diurnal cycle. Under these circumstances the ground-based observations would be inherently impractical for the photometric detection of small planets. With both photometric and spectroscopic data of high quality, and well determined noise properties on time scales of less than one hour, I have attempted (with dismal results) to derive useful information on longer time scales. I believe a FRESIP experiment on the ground is not possible.

With only minor modifications to the proposed FRESIP mission excellent auxiliary science could be expected for asteroseismology. Indeed FRESIP is close enough to ideal for asteroseismology that similar experiments might be proposed with stellar oscillations as the primary science driver.

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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:

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

Where $\delta\omega_{lmn}$ is the variation in the angular frequency with respect to the model frequency ω_{lmn}. $K_{A,Y}^{lmn}$ 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 (0.1μHz 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.

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THE SYMBIOSIS OF PHOTOMETRY AND RADIAL-VELOCITY MEASUREMENTS

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

1. Introduction

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

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

2. What do Radial Velocities Tell Us?

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

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

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

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

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

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

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

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

3. The McDonald Observatory Planetary Search

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

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

4. The Spectroscopic Survey Telescope

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

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

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

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

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

6. Summary

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

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Rotation Among Solar-Type Stars

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1. Introduction

The way in which stars like the Sun spin on their axes holds the key, we believe, to understanding virtually all observed manifestations of "activity." These manifestations include the x-ray emission seen by the Einstein and Rosat satellites, far-ultraviolet atomic emission lines from the chromospheres and transition regions of stars, as observed with the International Ultraviolet Explorer and the Hubble Space Telescope, and various spectroscopic signatures observed from the ground.

Our paradigm for describing this is that rotation interacts with convection in the outer parts of a star like the Sun, and the complex circulation that results leads to amplification of the magnetic field. This field is directly responsible for the activity and spots on the stellar surface. Also, the magnetic field can grip an ionized wind (like the solar wind) beyond the star's surface, leading to angular momentum loss and the gradual spindown of the star. We can see this process happening on the Sun, and we know that solar-type stars lose angular momentum as they grow older from studying stars in clusters whose ages are known. Another key parameter in understanding the generation of magnetic fields is the degree of differential rotation in the star, a parameter known with certainty only for the Sun.

It is also possible that the rotation of solar-type stars provides a critical clue to planetary formation. This is suggested by the fact that solar-type stars that have just reached the Zero-Age Main Sequence can rotate so fast that their total angular momentum is comparable to the combined angular momentum of the Sun and planets. This may only be a tantalizing coincidence; much more must be known of rotation first.

2. FRESIP

By obtaining high-precision photometry of a large sample of solar-type stars, FRESIP will be able to provide rotation periods for each of them. Our present knowledge of rotation in stars like the Sun is limited because blatant modulation of broadband light is only seen for heavily-spotted stars (the young and active ones). Our knowledge for the older solar-type stars — especially those at least as old as the Sun itself — is incomplete and imprecise because photometric variability is too slight to be seen from the ground and the line broadening from rotation is small and difficult to analyze. However, the Sun produces a detectable photometric signature of its rotation if it is observed with sufficient precision. This arises from sunspots crossing the solar disk, and we anticipate seeing the same effect on other stars. (Indeed, seeing no evidence for spots on a star like the Sun would be revolutionary in itself.)

A subset of the FRESIP sample could also be observed for evidence of p-mode oscillations, the fruits of which can yield fundamentally-determined ages for those stars. That, in turn, will enable the detailed study of the loss of angular momentum as a function of both mass and age, which will help us understand how the Sun got to be the way it is. Recent evidence suggests that solar-type stars go through a phase in their youth in which the radiative core rotationally decouples from the convective envelope, with gradual reconnection later. Again, the combination of p-mode data with directly determined rotation periods can precisely delineate this crucial phase.

3. Conclusion

The net result is that FRESIP will produce high quality rotational data for a large (and essentially volume-limited) sample of solar-type stars. Moreover, the observed slight changes in rotation period will indicate the nature and degree of differential rotation on those stars. Both parameters are central to our understanding of the evolution of the Sun.

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II. STELLAR VARIABILITY

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FRESIP Project Observations of Cataclysmic Variables – A Unique Opportunity

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Abstract. FRESIP Project observations of cataclysmic variables would provide unique data sets. In the study of known cataclysmic variables they would provide extended, well sampled temporal photometric information and in addition, they would provide a large area deep survey; obtaining a complete magnitude limited sample of the galaxy in the volume cone defined by the FRESIP field of view.

1. Introduction

If one reviews the many leaps of understanding that have been made in observational astronomy, it becomes clear that most of these have come about through many year efforts and dedicated observational programs. The classification of stellar spectra, the National Geographic/ Palomar Observatory Sky Survey, long term records of certain variable stars collected by the AAVSO, objective prism surveys for QSO's, and the Hubble guide star catalogue are but a few examples.

The FRESIP Project can provide astronomers with another leap into the understanding of planetary systems and could potentially provide humankind with much understanding about our existence, as well as simultaneously giving us a better view and understanding of our own galaxy and the universe beyond.

One of the unique opportunities available from the FRESIP Project is in the observational study of cataclysmic variables. These binary systems consist of a low mass red main sequence star in orbit about a white dwarf primary. The red star fills its Roche lobe and material flows through the inner Lagrangian point to usually form an accretion disk about the white dwarf. Some of these systems have highly magnetic white dwarfs in which the associated magnetic fields are so strong that the flow of material is interrupted and only an inner disk or even no disk at all is permitted to form.

Three basic types of CV exist. These are the dwarf novae (DN) which have fairly regular outbursts due to disk instabilities. These outbursts have amplitudes of usually 2-5 magnitudes but a larger amplitude group (with outburst amplitudes up to 10 magnitudes) exists. Novalike systems (NL) are similar to DN but are essentially always in outburst as they have a high rate of mass transfer. Finally there are the Novae (N) which undergo thermonuclear outbursts with long temporal spacing. Mass transfer rates from the secondary to the primary and the orbital period of the system are the basic causes for the different types of CV.

Low mass X-ray binaries (LMXRBs) are related systems in which the secondary can be a subgiant or giant and the primary is a neutron star or black hole.

In both cataclysmic variables and LMRXBs, there is a poor understanding of any temporal process. These systems are usually faint enough that they can not be monitored by amateur groups, are not easy to perform detailed studies on as they require large telescope time, and they spend most of their time in quiescence. Except for a few bright, somewhat well studied, probably nontypical systems, we are at a loss at understanding their behavior and evolution. This is unfortunate for astronomy, as CVs are very good laboratories for accretion studies. They undergo changes on minute to hour to daily to longer timescales, accretion and accretion disks are important for our understanding not only of CVs, but also our understanding of accretion processes in other astrophysical objects such as AGNs and newly forming solar systems.

In the following paper, I emphasize the need and value of essentially complete temporal monitoring of CVs that the FRESIP telescope could provide. The types of data sets which would be available divide up into two major areas; 1) A well sampled temporal study of known or newly discovered CVs within the FRESIP field of view (FOV) and 2) A deep survey conducted in some test areas within the FRESIP FOV. This second dataset would be of use to persons wishing to obtain deep surveys of extragalactic objects, studies of other possibly yet unknown faint or transient phenomena, and studies that would help our understanding of CCDs as instruments capable of observing low S/N objects and long-term operation in a space environment.

2. Temporal Studies of Cataclysmic Variables

The best long term time series data sets that are available for CVs to date, are visual and photoelectric measurements of CVs. These lightcurves are mostly obtained by amateurs belonging to the AAVSO or other equivalent organizations. These, of course, have a number of flaws such as 24-hour alaising, large uncertainties, and the limiting magnitude is usually brighter than about 12th magnitude.

Cannizzo and Mattei (1992) for example, have presented the entire almost 100 year lightcurve of SS Cygni. Even thought this represents a milestone in the study of CVs, it still is incomplete in two ways. It represents only one CV, and possibly a non-typical one at that, there are gaps in the data of days (> 10 days at times), and at particularly important places, such as the fast rise to outburst. These problems are in addition to those already stated above.

Richter (1992) shows outburst lightcurves for a few large amplitude DN. These lightcurves are from Sonneburg Observatory plates but are typical of data of this sort from any of the observatory plate collections; they are missing data for various reasons, have uncalibrated plate materials, and as above, the limiting magnitude is usually not very faint (about 16-17th magnitude). In his work, Richter discusses some interesting features seen in the outburst decline lightcurves. Interpretation of these gaps is very important to our understanding of the outburst physics, yet it is very difficult due to lack of contiguous data points.

We do not have complete coverage of the entire outburst of many kinds of

CVs, and Howell (1993) has shown that there are many faint CVs with large amplitude outbursts for which we have just a single datum. These same stars have essentially NO information during minimum light due to their faintness and there is evidence (Howell et. al. 1990) that many such systems have large variations during quiesence as their mass transfer rate changes with time. Only a long-term, well sampled data set can answer all the above questions.

Photometric studies of CVs can be roughly divided up into four regimes: 1) quiescence, 2) the outburst cycle (rise-maximum-decline), 3) the longer term cycle to cycle variations, and 4) quasi-periodic oscillations (QPOs). We have a fairly good understanding for some systems of regime 2 but only sketchy information on various systems in the others. No complete picture exists and it is unlikely it will without data from the FRESIP project.

To demonstrate what can be accomplished with a long-term photometric study, I will use an example based on a 4-year ongoing project to study an LMXRB. The star V404 Cygni underwent an outburst in May 1989. It had been listed as a classical novae since its last outburst in 1938. Wagner et al. (1992) showed the system to have an orbital period near 6.5 days and a black hole primary of 8-12 solar masses. Photometric information was collected over many nights by myself and my colleagues.

Using nearby stars within the same FOV, and pooling all the data, nearly 3000 data frames, we were able to detect the 0.2 mag full amplitude in the lightcurve orbital modulation and are finally beginning to understand the many other detailed photometric variations within this system. Quasi-periodic oscillatories have been a source of confusion and frustration for CV workers for many years. Data from a single night or even many nights observation can produce spurious frequencies within a power spectrum to fool the observer. The papers of Patterson and Thomas (1993) bear testimony to the observational difficulties of QPO studies.

The origin of these quasi-periodic oscillations is of great importance to theoretical studies. The origin and nature of why certain frequencies are preferred in certain systems is a complete mystery. The large stumbling block to date has been the need for finding and positively identifying QPOs.

Figure 1 shows sample frequency spectra for constant comparison stars and our current frequency spectrum on V404 Cyg in which we can clearly identify the many QPOs that exist in the system. Remember that this frequency spectrum is based on more than 4 years of ground-based photometric data and is marred by daytime data losses and weather interruptions. We are now able to provide, for this one system, the data needed for better models of accretion mechanisms and binary structures in black hole systems.

The current targeted FOV of the FRESIP telescope contains 6 known CVs (Downes and Shara 1993). Photometric information of these objects in 'white light' will reveal much needed new information of the nature of CVs. The study of these stars alone with data taken every hour for many years would dramatically improve the data-base for CV research.

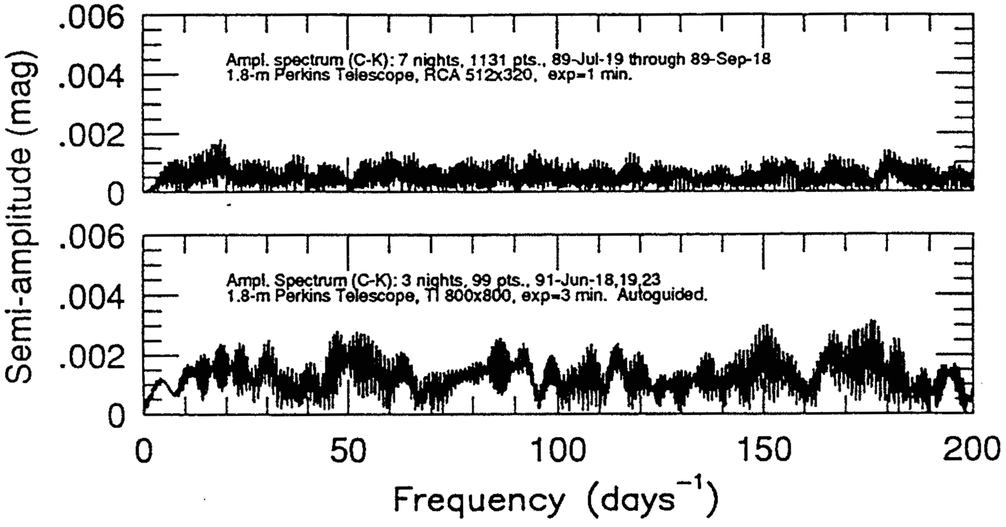

Figure 1A. Frequency Spectrum of assumed constant comparison stars used in the study of V404 Cygni. The two comparison stars C and K used in the bottom panel are about 3 magnitudes fainter than those in the top panel. Note that the number of observations used and time coverage are not the same. Adapted from Kreidl (1992).

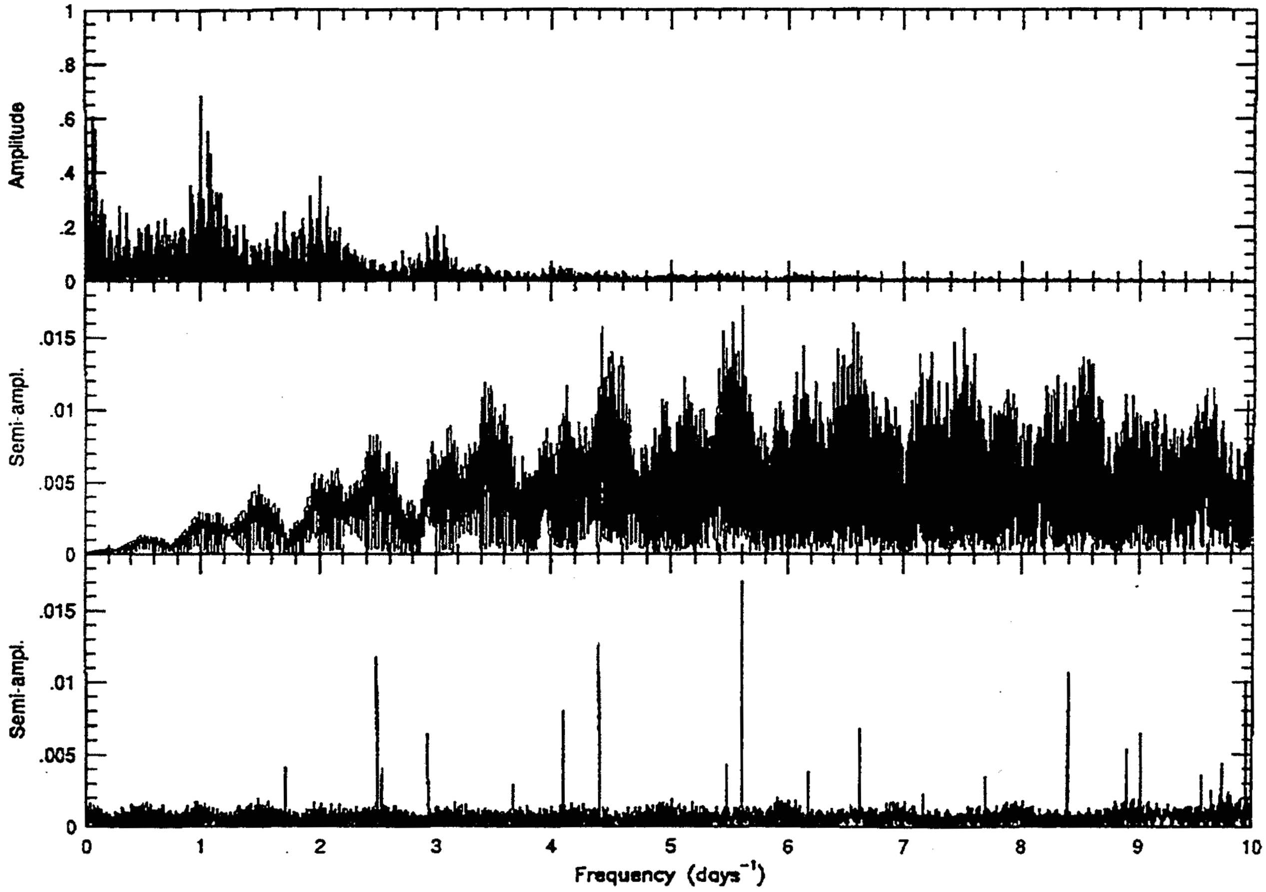

Figure 1B. Frequency Spectrum for the Black Hole LMRXB V404 Cygni. The top panel shows the spectral window, the middle panel is the raw spectrum and the bottom panel in the cleaned spectrum. Note the presence of many significant periods.

3. The FRESIP Deep Cataclysmic Variable Survey

The study of CVs, since their "discovery" as a class of star in the mid-fifties, has lead to a list of ~500 known systems. Of these, only about 1/4 have a known orbital period and any other associated detailed information. It has become apparent in recent years (Howell and Szkody 1990, Howell 1993) that the well known and well studied systems, the brightest and closest ones, are likely to be atypical of the entire population of CVs. Howell (1993) has provided evidence which suggests that there may be an entire population of low luminosity CVs which have very faint minimum magnitudes (18-22+), and are rarely observed due to their infrequent, yet large, outbursts.

The collected information on the current well studied systems may be leading us to a false conclusion about the entire population of CVs in general. Surveys to find these fainter systems have been limited to very small areas of the sky and single epochs. They usually employ 2-color techniques (looking for blue objects) in an attempt to isolate candidates. Other methods have been literature searches for randomly seen outbursting systems and then attempted follow-up studies to try to identify the candidate stars.

Long-term, deep survey data is badly needed. Many CVs are NOT blue most of the time. Most CVs spend the majority of their time at (faint) minimum, and single epoch snapshots will miss any indication of orbital variation or other photometric signatures. The long-term luminosity of these stars is also of interest as they are likely to have their mass transfer start and stop stochastically. Studies of the nature of mass transfer will provide information on how binaries evolve, the thermal evolution of the secondary star, and binary dynamics.

If these fainter systems exist in abundance as appears likely from recent clues (Shara et al. 1993), then the current beliefs on the space density of CVs must be revised. This large increase in numbers of binary systems would have important implications to CV evolution, binary star formation rates, and the evolutionary status of stellar systems in our galaxy.

In order to determine how the FRESIP Project could be used for such a deep survey, I have run simulations for the FRESIP telescope based on a 1m aperture and use of a broadband filter. A larger telescope using unfiltered light will give higher S/N values for a given integration time. These are shown in Figure 2. Figure 2A shows the predicted S/N obtainable for four sample magnitudes in a 1 hour exposure. We see that stars of even 20th magnitude are easily detectable and their variability deduced. Figure 2B shows the same information but for a single 24-hour period. We are now able to begin to detect 24th magnitude sources. Over only a small time span compared to the mission lifetime, variable objects at quite faint magnitudes will be easily detectable. Detection of serendipitous CVs and supernovae in background galaxies should also occur. Over many years, FRESIP will provide us with a complete sample of variable sources such as CVs, to a limiting magnitude which should detect all unobscured CVs in the volume cone, defined by the FOV, within our entire galaxy.

The FRESIP Project will provide photometric information showing orbital modulations and other variations for many CVs. These would be the first such data sets and be of a unique nature.

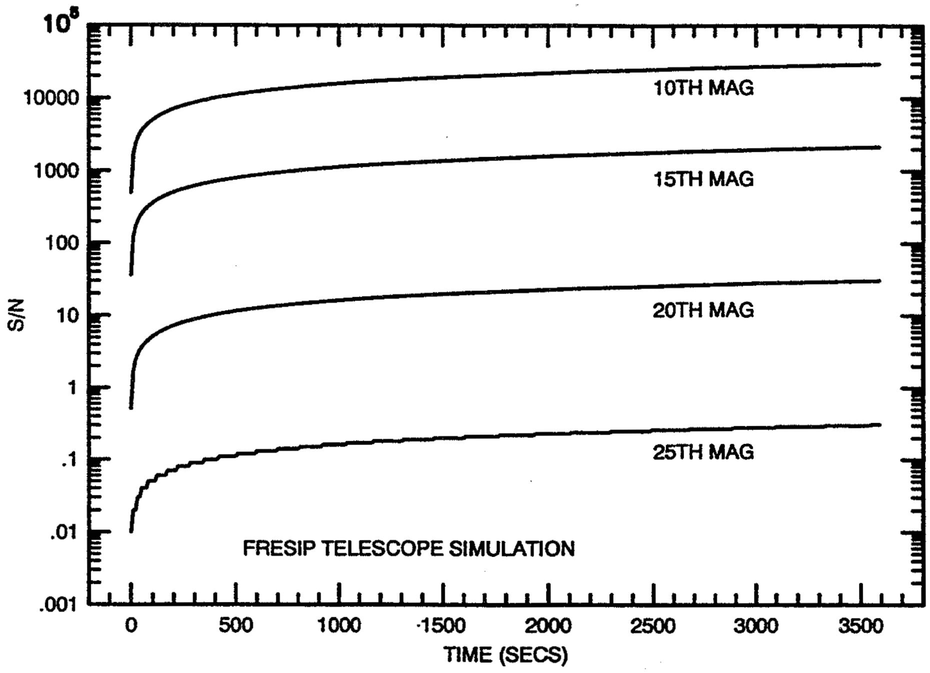

Figure 2A. Simulations of the S/N obtainable with the FRESIP telescope during one hour of observation.

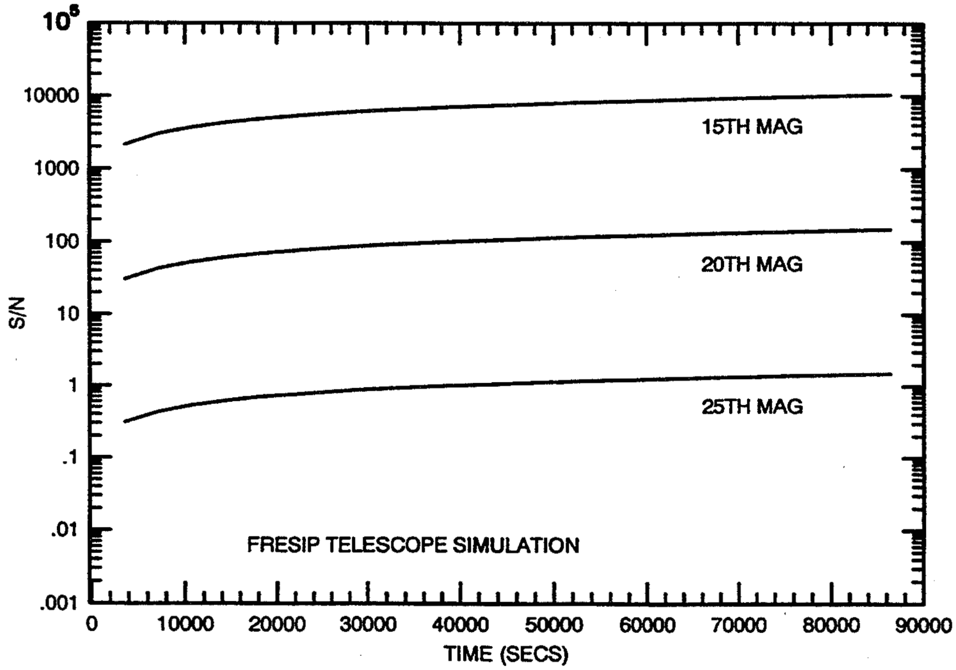

Figure 2B. Simulations of the S/N obtainable with the FRESIP telescope during one day of observation.

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OBSERVATIONS OF HOT STARS AND ECLIPSING BINARIES WITH FRESIP

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ABSTRACT

The FRESIP project offers an unprecedented opportunity to study pulsations in hot stars (which vary on time scales of a day) over a several year period. The photometric data will determine what frequencies are present, how or if the amplitudes change with time, and whether there is connection between pulsation and mass loss episodes. It would initiate a new field of asteroseismology studies of hot star interiors. A search should be made for selected hot stars for inclusion in the list of project targets. Many of the primary solar mass targets will be eclipsing binaries, and I present estimates of their frequency and typical light curves. The photometric data combined with follow up spectroscopy and interferometric observations will provide fundamental data on these stars. The data will provide definitive information on the mass ratio distribution of solar-mass binaries (including the incidence of brown dwarf companions) and on the incidence of planets in binary systems.

1. Hot Star Variability

There is growing evidence that many O- and B-type stars are nonradial pulsators (NRP) with periods on the order of a day (Baade 1987; Fullerton 1991; Cuypers 1991; Walker 1991). This time scale is problematical for ground-based observers, and we have only a preliminary notion of the pulsation characteristics of massive stars. Continous photometric monitoring of these stars over several years would lead to a vast improvement in our understanding. Many objects are known to be multi-periodic (Smith 1985; Gies & Kullavanijaya 1988; Waelkens 1991), and I suspect that most will turn out to be multi-periodic. However, to approach the kind of results found for white dwarf pulsations, where observers can obtain continuous data over 1000 cycles (cf. Winget et al. 1992), would require 2 years of continous monitoring for a Be star pulsator like λ Eri (Balona et al. 1992). The great attraction of studying NRP in hot stars is that in most cases the stars are rapid rotators, and consequently the rotational Doppler line broadening reflects the longitudinal distribution of the pulsations across the visible hemisphere. Thus combined spectroscopic and photometric studies can lead to the detection of relatively high-order pulsations.

There are many potential scientific gains from continuous monitoring. The following are some representative cases involving time scales on the order of a day:

Be stars: Most Be stars display line profile variability consistent with low order NRP (Baade 1987), and the same periods are found in the photometry ($\Delta m \approx 0.05$ mag; Percy 1987). Both the photometric amplitude and Be emission activity vary on time scales of months to years. Since NRP is a potential source of energy to promote mass loss into a circumstellar disk, it is important to search for a correlation between pulsation activity and Be emission episodes.

O stars: A few O stars are known multi-periodic line profile variables (cf. ζ Oph, Reid et al. 1993). The stars are also photometric variables but the variations are complex (termed "microvariability"; cf. Balona 1992).

Slowly pulsating B stars: A growing number of B stars are found to be multi-periodic, photometric variables (cf. 53 Per, Buta & Smith 1979; Waelkens 1991). Beating between the signal frequencies can only be sorted out over very extended time scales (often longer than a typical observing season).

The long periods indicate the presence of g-mode pulsations which should represent an important probe of hot star interiors. Saio & Lee (1991 and references therein) show that NRP in Be stars could result from coupling with convective motions in the core; thus the phase motion of NRP in the photosphere reflects the core rotation rate. Data accumulated over several years would provide the means to begin significant asteroseismology studies of hot star interiors.

2. Hot Star Content in the Selected Region

Are there interesting hot star targets in the regions near $(l,b) = (90°,+15°)$ or $(l,b) = (89°,+11°)$? Unfortunately, the massive star population dwindles rapidly at high Galactic latitudes, so the sample will be limited. There are no O stars with $V < 9.0$ in these regions (Cruz-González et al. 1974). Since $V = 9.0$ corresponds to a height of $z = 1$ kpc for an O8 V star at $b = +15°$, and since the the scale height for O stars is 73 pc, there will be few if any O stars found in the proposed fields of view (FOV). There is one B5 V star, HD 188665 (HR 7608 = 23 Cyg), near the center of the $b = 15°$ FOV. The *Bright Star Catalogue* (Hoffleit 1982) lists the star as a possible velocity variable, so this may be a pulsator. There are several known B stars in the $b = 11°$ FOV (HD 195554, HD 196421, and the Be star HD 194883). However, all these stars are bright ($V < 8$), so a neutral density filter would be required.

I expect that there are many fainter B stars that remain undetected in these fields. The number of B stars, N, fainter than some limiting V_b can be estimated from

$$N = \Delta\omega \; \rho_\circ \; \alpha^{-3} \; e^{-\alpha r}\Big((\alpha r)^2 + 2\alpha r + 2\Big),$$

where $\Delta\omega$ is the angular area of the field, the local space density of B stars is $\rho_\circ = 1 \times 10^{-4}$ pc^{-3} (Mihalas & Binney 1981), α is the ratio of $\sin b$ to the scale height $\beta = 69$ pc (Abt 1987), and r is the distance corresponding to V_b. The extinction is $A_V = 0.64$ (1.66) mag in the $b = 15°$ (11°)

FOV (Burstein & Heiles 1982); thus, for $V_b = 10$, the distance of a B3 V star (with $M_V = -2.0$) is $r = 1870$ (1170) pc. Therefore, the number of B stars in the FOV fainter than $V = 10$ is ≈ 37 (92); $\approx 18\%$ of these will be type Be (Abt & Cardona 1984). Thus even after deletion of the bright stars (and the need for neutral density filters), there will be a significant number of targets for study.

The great potential of continous monitoring with the FRESIP mission could easily be extended to this sample of B and Be stars in the FOV. Such targets should be selected by spectroscopic observations of blue objects in the FOV.

3. Eclipsing Binaries among the Main Targets

Many of the solar mass targets of the FRESIP program will be eclipsing binaries with stellar companions. The light curve data on these systems will provide fundamental data (masses and radii) when combined with spectroscopic data.

Mayor et al. (1992) report on the binary properties of a volume limited sample of G- and K-type main sequence stars (from CORAVEL radial velocity measurements of some 900 stars over a time span of > 10 years combined with visual binary and common proper motion data). They find that the period distribution has a Gaussian shape in log P (mean period of 170 y). The mass ratio distribution is approximately flat but they argue that the numbers could rise at the low mass end.

The period distribution can be transformed to a semi-major axis distribution for an assumed mass ratio. This in turn can be used to obtain a probability distribution for a stellar eclipse. This probability distribution is illustrated as a function of semi-major axis a in Figure 1. The integrated probability of finding an eclipsing system at any a is 0.4% (or 0.9% according to the binary frequency found by Abt & Willmarth 1992). This result is essentially independent of the assumed mass ratio. The lower limit for the integration, $a = 2\ R_\odot$, probably represents a contact binary (Mochnacki 1981). The mean observed semi-major axis for these eclipsing systems is 0.13 AU ($P = 14.6$ d).

I have calculated eclipse light curves (V-band) for several types of companions. These models take $P = 14.6$ d and $i = 90°$, and assume that the primary is a solar mass star with the Sun's radius. The assumed flux (Kurucz 1970) and limb darkening law (Wade & Rucinksi 1985) for the solar mass primary were taken from a $T_{\rm eff} = 5500$ K and $\log g = 4.5$ model atmosphere. The input parameters and eclipse depths (Δm_p for primary superior conjunction) are given in Table 1. The full duration of the eclipse is given by Δt.

The K star model light curve illustrated in Figure 2 was made with the synthesis program of Mochnacki & Doughty (1972). The model flux and limb darkening for $T_{\rm eff} = 4000$ K and $\log g = 4.0$ were taken from Carbon & Gingerich (1969). Both primary and secondary eclipse are easily visible.

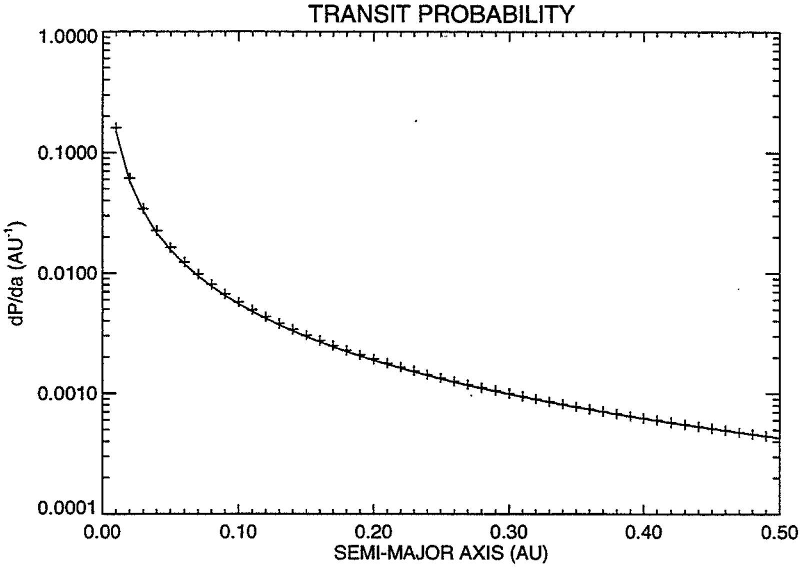

Fig. 1.— The probability of a transit of the center of a star across a solar mass dwarf as a function of a (based on the period distribution of Mayor et al. 1992). The solid line shows the distribution for a mass ratio $q = M_2/M_1 = 1$ while the plus signs show the nearly identical distribution for $q = 0$.

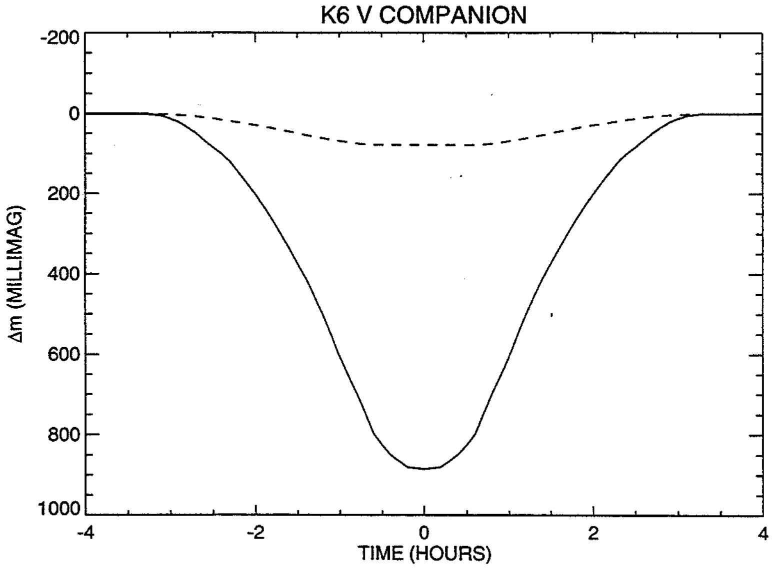

Fig. 2.— The primary (*solid*) and secondary (*dashed*) eclipses of a K-dwarf around a solar type star.

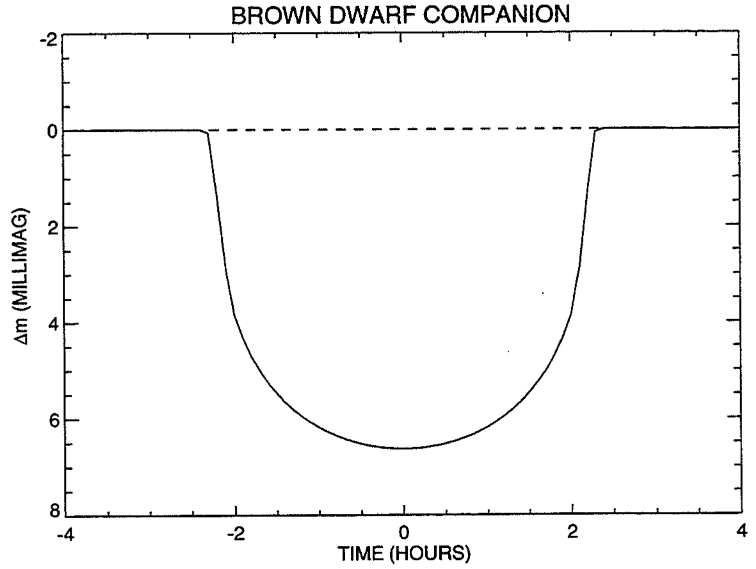

Fig. 3.— The primary (*solid*) and secondary (*dashed*) eclipses of a late M-dwarf (or brown dwarf) around a solar type star.

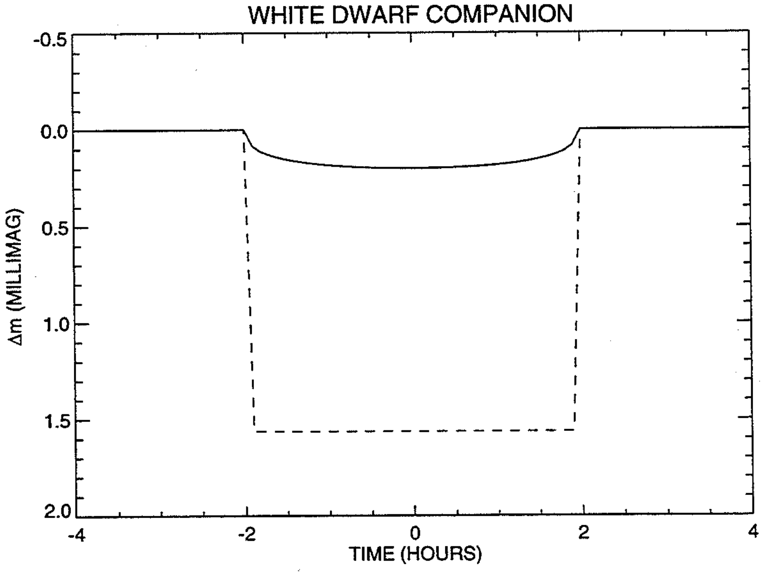

Fig. 4.— The primary (*solid*) and secondary (*dashed*) eclipses of a DA white dwarf around a solar type star.

An eclipse by a late M-dwarf or brown dwarf is shown in Figure 3. Parameters for a possible brown dwarf companion were taken from Kirkpatrick et al. (1993) for GD 165B. For this case (and the next), a simple analytical light curve was used. A star this faint acts only as an opaque disk; no secondary eclipse is seen. The variation during primary eclipse reflects the limb darkening of the solar mass primary (thus the shape of the eclipse should help determine the inclination).

Finally I calculated an eclipse for a white dwarf star (Fig. 4). Parameters for a DA white dwarf companion were taken from Bergeron et al. (1992) for $T_{\rm eff} = 11000$ K and log $g = 8.0$. Because of the larger surface flux of the hotter white dwarf, the secondary eclipse (white dwarf behind) is the deeper one in this case.

The final column in Table 1 lists the amplitude of the reflex motion that would be observed in the solar mass star. Each of these cases would be detected with high resolution spectroscopy, and the combined light curve and spectroscopic data would yield the inclination and limits on the masses (masses follow if the system is double-lined or a mass estimate is made for the primary). Precise secondary radii could also be determined with a time resolution better than $\Delta t = 1$ hour.

The FRESIP data will yield a definitive mass ratio distribution for solar-mass binaries. This will be of crucial importance in determing the frequency of low mass stellar or brown dwarf companions. If any of these eclipsing binaries also host planetary systems, then it is probable that planetary transits will also be observed since the stellar and planetary orbital planes are likely to be nearly coincidental. Thus the FRESIP program will provide key data on the occurrence of planets in binary systems.

Table 1. MODEL ECLIPSE DEPTHS

Star	M ($M_\odot$)	R ($R_\odot$)	Flux Ratio (F_s/F_p)	Δt (h)	Δm_p (mmag)	Δm_s (mmag)	K_1 (km s^{-1})
K6 V	0.64	0.718	7.5×10^{-2}	6.5	885	79	40.1
GD 165B	0.08	0.069	2.6×10^{-4}	4.6	6.6	2.8×10^{-5}	6.6
DA	0.52	0.012	1.4×10^{-3}	3.9	0.20	1.56	34.2

4. Complementary High Angular Resolution Studies

Over the next decade many close binaries will be resolved with optical interferometers. The Center for High Angular Resolution Astronomy at Georgia State University (H. A. McAlister, Director) is completing plans for the CHARA Array, a 7-element optical/IR interferometer with a 400-m baseline. This telescope will resolve binaries down to separations of 0.2 milliarcsec and magnitude differences of $\Delta m = 3$ (for objects with $V < 12$). For solar-type targets of $V = 10$ at a distance of 100 pc, all binaries with $P > 0.8$ d will be resolved. Such binaries will probably be double-lined systems, and the combination of interferometric, spectroscopic, and light curve data will yield accurate inclinations, masses, radii, and distances to the systems. The CHARA Array will also be used to search for Jupiter-sized planets in wide binaries by measuring reflex motion in the residuals from the binary orbit.

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III. EXTRAGALACTIC OBJECTS

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MONITORING THE VARIABILITY OF ACTIVE GALACTIC NUCLEI FROM A SPACE-BASED PLATFORM

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1. INTRODUCTION

Active galactic nuclei (AGNs) are among the most luminous detected sources in every waveband in which they have been observed. Their bolometric luminosities are typically in the range $10^{11-14}\,\mathrm{L}_\odot$. However, the mechanism by which the emitted energy is generated is not yet understood. The nearly 30-year-old paradigm is that the energy is produced via thermal viscosity in an accretion disk surrounding a supermassive (typically $\gtrsim 10^7\,\mathrm{M}_\odot$) black hole. While gravity accounts for most of the energy production, magnetic fields are also thought to play a role in at least some AGNs by collimating a relativistic outflow of radio-emitting plasma. The accretion-disk hypothesis remains unproven because the expected signatures of the process are somewhat ambiguous and the models are not well-constrained by the observations. However, it is increasingly recognized that continuum variability provides one of the most direct probes of the energy-generation process. AGNs are known to vary dramatically across the entire observable electromagnetic spectrum, from γ-ray to radio energies, and it is only relatively recently that we have begun to exploit the variability characteristics of AGNs to probe the central regions.

For the purposes of this discussion, we will distinguish between two types of AGN, "normal AGNs" and "blazars," since the variability characteristics of the two types are quite different. Current thinking, as embodied in what are referred to as "unified models" (Antonucci 1993), holds that the apparent difference between the two types is due only to the aspect angle at which they are observed: blazars are simply AGNs that are observed along or very close to the radio axis so the detected flux is dominated by the relativistically beamed nonthermal radiation (synchrotron self-Compton) that arises in the radio jets. In the case of normal AGNs (Seyfert galaxies and non-beamed quasars), virtually all of the emission between the satellite ultraviolet and the submillimeter is ascribed to thermal processes. The spectral energy distribution of normal AGNs shows a broad peak, the "big blue bump" (BBB) rising shortward of ~4000 Å and dropping off at energies less than ~1 keV (there is debate as to whether the BBB extends into the the soft X-ray band), which is usually supposed to be the signature of the accretion disk (Shields 1978; Malkan & Sargent 1982). In this scenario, UV/optical continuum variability is ascribed to accretion-disk instabilities (lower-amplitude, short-time scale variations) and to changes in the mass accretion rate (larger amplitude variations over longer time scales). However, it can also be argued that the BBB is due to optically thin bremsstrahlung rather than optically thick thermal emission (e.g., Barvainis 1993); this is more of a phenomenological argument, since the driving mechanism has not been identified. In principle, detailed observations of continuum variability, even in a single waveband, can provide a constraint on the physical mechanisms that might be at work in either optically thick or optically thin models.

In the case of blazars, continuum variability time scales and observed source brightness temperatures provide a strong constraint on the Doppler-beaming factors and thus yield strong lower limits on the source energetics.

2. PREVIOUS OBSERVATIONS

There have been few sustained programs to study systematically UV/optical variability in AGNs. The longest running program of which we are aware is the program of photographic photometry which has been undertaken by A.G. Smith and collaborators at the University of Florida for about two decades. The use of photographic detectors limits the accuracy of the photometry to ~10%, which is adequate for for studying the large amplitude variations (often more than a magnitude) seen in blazars, but of less utility for normal AGNs, where the rms variability over a year is typically only around 30%. Moreover, the temporal coverage that can be achieved at an inferior ground-based site is not sufficient to resolve the most rapid variations for either blazars or normal AGNs.

Until a few years ago, very little was known about the continuum variability characteristics of normal AGNs. This situation has changed on account of multi-wavelength emission-line reverberation mapping experiments that have been carried out with *IUE*, *HST*, and ground-based telescopes. The optical continuum light curve for the best observed normal AGN, NGC 5548, is shown in Fig. 1. Only a handful of normal AGNs have been observed in any detail, and in many cases they have been *preselected* based on earlier observations that showed they varied with amplitudes and time scales suitable for reverberation mapping experiments. Any generalizations based on existing results are thus highly suspect since it is not known how representative these highly variable sources may be of AGNs as a class. Furthermore, even the

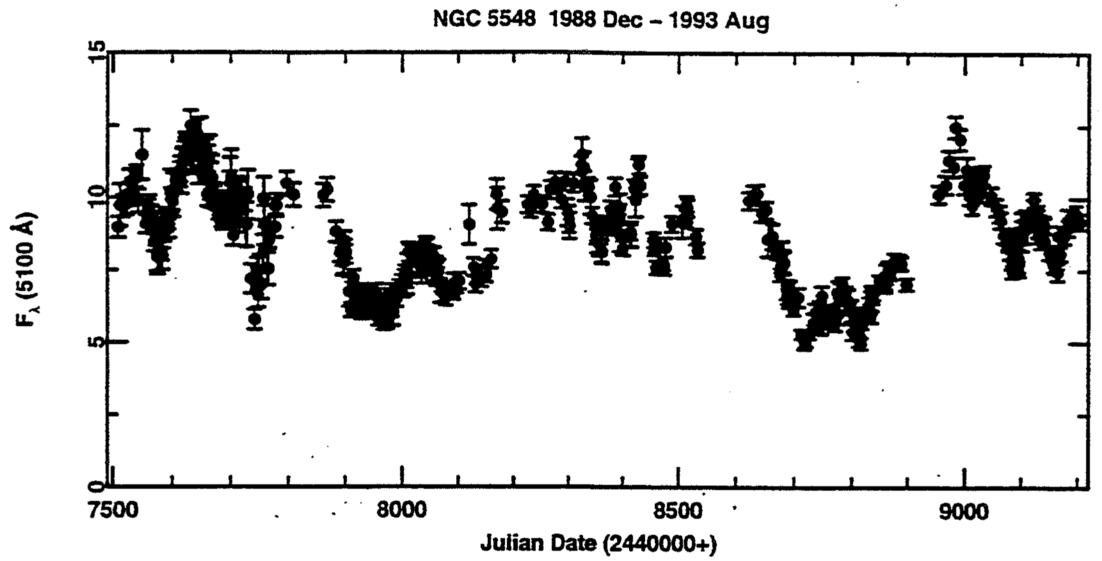

Figure 1: Optical continuum (5100 Å) light curves from the International AGN Watch monitoring of the Seyfert 1 galaxy NGC 5548. Fluxes (in the rest frame NGC 5548) are in units of 10^{-15} $\mathrm{ergs\,s^{-1}\,cm^{-2}\,Å^{-1}}$. The average interval between observations is approximately 3 days and the typical error level is about 4%. Measurements from Peterson (1994) and unpublished International AGN Watch data.

best available variability data suffer from limited temporal coverage: ground-based coverage tends to be irregular due to telescope scheduling difficulties and unpredictable weather, and space-based coverage is usually limited in duration by solar proximity or spacecraft positive-power constraints. The most complete space-based programs (typically with time resolution of a few days) have run only about eight months (Clavel et al. 1991; Reichert et al. 1994). A program of continuous monitoring of NGC 4151, with time resolution of about 90 minutes, is scheduled for early December 1993, but the continuous coverage will last less than 10 days.

Another phenomenon that has received some attention over the past few years is that of *microvariability*, small amplitude ($\gtrsim 0.1$ mag) UV/optical variations which occur in blazars on time scales of hours. The best observations to date are those of BL Lac object PKS 2155–304 which were obtained in a massive campaign in 1991 (Urry et al. 1993).

Some of the existing data for both blazars and normal AGNs *suggest* the existence of periodic or quasi-period variability, indicative of the possible importance of orbital motion. The evidence for any periodicities is *very* marginal because the time series of observations are too short. Nevertheless, it is important to search for characteristic time scales because of the implications that their existence (or nonexistence) would have for our understanding of the AGN phenomenon.

The fluctuation power density spectrum, or PDS (a measure of variability power as a function of temporal frequency), is of great potential use if both high enough and low enough temporal frequencies are explored. A PDS determined from UV/optical variability has been published for a normal AGN in only one case, NGC 5548, based on data obtained as part of the *IUE* monitoring campaign of 1988–89 (Krolik et al. 1991). These data show that the PDS is relatively steep ($P(f) \propto f^{-(2-3)}$). but the dynamic range over which the PDS is measured is only a factor of ~4, in the frequency range (120 days)$^{-1}$ to around (30 days)$^{-1}$. This range is insufficient to detect turnovers in the power spectrum at either the high or low frequency end.

It should also be mentioned that on-going searches for MACHOs will provide data that can used to examine continuum variability in a large number of AGNs. Both the potential number of AGNs that can be studied and the duration of the experiment are comparable to what is envisaged for the FRESIP mission, but by comparison the MACHO survey data will be of much lower signal-to-noise ratio (a factor of about 10 lower at the faint end, where most of the AGNs will be detected), and the data will be more irregularly sampled on account of interruptions due to weather and seasonal gaps.

3. Monitoring AGN Variability with FRESIP

3.1. Science Goals

A space-based observing platform such as FRESIP that is designed to carry out a multiyear monitoring program on a large number of sources in a fixed field affords an unprecedented opportunity to study AGN continuum variability. At least two very general questions can be addressed:

1. *Are there characteristic time scales or power density spectra for AGN variability?* With long, evenly sampled time series, that can *only* be obtained with space-based telescopes, it will be possible to search for characteristic frequencies and to determine the power density spectra of AGN variability with much greater confidence than has been done in the past. The temporal frequencies for sources observed with the FRESIP telescope in principle extend from ~(3 year)$^{-1}$ to ~(0.1 day)$^{-1}$, i.e., a dynamic range of 7×10^4.

2. *As a class, how do AGNs vary?* Surprisingly, there is virtually *no* reliable information on the statistics of AGN variability – there is insufficient existing information to answer simple questions such as what fraction of AGNs with luminosity L will vary by an amount larger than δL in some time Δt? These sorts of considerations are crucial in understanding correlations involving AGN

luminosities, such as the Hubble diagram and the Baldwin effect. The existing data, usually based only a handful of observations of several sources, are consistent with virtually *all* AGNs varying detectably on time scales less than a year or so. Only a very few AGNs have been studied in detail, and those sources have often been selected for study *because of* their variability.

3.2. Technical Feasibility

In this section, we make a statistical estimate of how many AGNs one might be able to monitor with the baseline FRESIP design in a mode that is compatible with the primary science objectives of the mission. Note that many of the considerations adressed here apply generally to faint objects that might be observed with FRESIP, such as cataclysmic variables (cf. Howell, these proceedings).

We note the following specific points:

1. We will assume that the minimum acceptable signal-to-noise ratio $(S/N) = 100$; this significantly exceeds the quality of data that currently exist and there is no obvious reason to push for much higher S/N to detect variability that is energetically not especially important. While lower S/N data would still have some value, they would not be markedly better than what one could obtain from the ground. The advantage of FRESIP's rapid time resolution would be lost by compromising further on the allowable S/N.

2. We will assume that the minimum temporal resolution is 1 hour. On the basis of what is known about AGN variability, this is more than sufficient, even for microvariability studies. For virtually all AGNs, the FRESIP telescope will operate in the background-dominated regime so further improvement in signal-to-noise ratio S/N can be obtained by summing over many hours, in which case $S/N \propto t^{1/2}$, where t is the total exposure time.

3. The FRESIP field (at Galactic coordinates $\ell = 90°$, $b = 15°$) is not optimal for extragalactic studies as the foreground extinction is not negligible and quite variable across the field (in the range $0.1 \lesssim E_{B-V} \lesssim 0.5$, with a typical value of $E_{B-V} \approx 0.2$; Burstein & Heiles 1982), but nevertheless usable. The sky background is assumed to be quite low ($\mu_V \approx 22\,\mathrm{mag\,arcsec}^{-2}$) since the field center is near the north ecliptic pole (avoiding much of the zodiacal light contribution) and not too close to the Galactic equator (where the background due to unresolved stars becomes important).

4. For parameters that are likely to change somewhat in the final design, we assume $24\,\mu$m pixels, a pixel scale of $2''.6\,\mathrm{pix}^{-1}$, and that each image will cover 9 pixels. This translates to a field of view of about $7^\circ.4$. We will assume that the read-out noise per subintegration is $50\,\mathrm{e}^-\,\mathrm{pix}^{-1}$.

Given the baseline assumptions about the telescope/detector system (i.e., 1-m effective aperture, 80% throughput, detector quantum efficiency of 50% over the range 450 – 850 nm, and 2.3 sec subintegrations, we find that the read-out noise exceeds the background noise by a factor of ~7.1, and that both these sources of noise exceed the uncertainty introduced by source photon statistics for all cases but the very brightest AGNs (none of which are present in this field). We find that we expect to be able to detect AGNs as faint as $V = 19.6\,\mathrm{mag}$ at $S/N = 100$ in an hour. Adjusting for foreground extinction ($A_V = 0.6$) and assuming a mean color $B - V \approx 0.4$, this corresponds to $B = 19.4\,\mathrm{mag}$ in an unreddened field. Koo & Kron (1988) find that the total surface density of AGNs is $\sim 100\,\mathrm{degree}^{-2}$ to a limiting magnitude $B = 21.1\,\mathrm{mag}$. Thus, the surface density to $B = 19.4\,\mathrm{mag}$ is approximately $9.5\,\mathrm{degree}^{-2}$. Assuming a field of view of $7^\circ.4$ and a correction factor of 0.8 for detector gaps and flaws gives an expected number of suitable targets

$$N_{expected} \approx 330.$$

Although this seems like a suitably large sample for an AGN variability study, we note the following:

1. As one approaches the faint end of the distribution (where one finds the great majority of the targets), *source confusion* might become a serious problem for such large images. The individual targets need to be examined carefully on high-quality images to make sure that the target can be photometrically distinguished from other nearby objects (mostly faint foreground stars) at low angular resolution.

2. As always in faint-object astronomy, the background must be measured accurately. A suitable number of "blank fields" must also be measured to determine the background level.

The calculation made above assumes a gain of unity, i.e., that $1\,\mathrm{ADU} = 1\,\mathrm{e}^-$. This presents a problem if the entire electron well depth is to be used for the bright objects and the number of bits in the A/D converter is small. For example, if the full well per pixel is $5 \times 10^5\,\mathrm{e}^-$ and a 14-bit A/D converter is used, then the required gain is $5 \times 10^5/2^{14} \approx 30\,\mathrm{e}^-$ per ADU. We will decrease this slightly to 25 so that the read-out noise is well sampled. We require that the digitization process not limit the signal-to-noise ratio at the faint end, i.e., the number of counts per read-out must exceed

$2S/N$. For $S/N = 100$, we find that we are limited to $V \lesssim 16.2$ mag. The expected number of AGNs in the field thus becomes very small (only about 10). High-quality well-sampled light curves for even a *very few* AGNs would be valuable, despite the loss of statistical information. However, it is in principle possible to overcome this limit by changing the gain in software for each local-area read, and this should be done for the fainter objects. Several other pixel-to-pixel changes can be programmed to increase S/N since the signal level in each pixel is known *a priori* to a fraction of a percent.

3.3. Target Selection

Because of its proximity to the Galactic plane, the proposed FRESIP field has not been well-surveyed for AGNs. A search of the major AGN catalogs (Véron-Cetty & Véron 1989; Hewitt & Burbidge 1987, 1989) reveals that there are *no* known AGNs in the FRESIP field, although there are several fairly bright AGNs within about 15° or so of the field center. Clearly the field will need to be surveyed in detail prior to launch to search for AGNs, as well as other sources. The AGNs can be isolated through multicolor imaging and/or objective prism spectroscopy, and the search strategy will depend to some extent on how deep one wishes to go. A prelaunch survey of the field will require significant lead time, and this should be taken into consideration in the early stages of project planning.

4. ALTERNATIVE DESIGNS

We have given further consideration to how some of the baseline parameters might be altered to enhance the AGN variability experiment, in part to emphasize the impact various trade-offs will have on faint-object secondary science. Since AGNs are faint sources, the quality of the observations is background-limited. Therefore, a significant improvement can be realized by better focusing of the telescope; since AGNs are all faint, saturation of targets is not a concern. (For a mission optimized for an AGN study, the brightest stars would need be be masked out, or detectors with effective anti-blooming characteristics would be required.) In order to enhance the performance of a telescope in the proposed orbit for AGN monitoring, we would recommend the following changes:

1. The telescope should be focused to optimize the contrast of the point sources relative to the background. The telescope should be able to operate at the diffraction limit.

2. Since we are now considering monitoring fainter objects, we will increase the individual integrations from 2.3 seconds to something like 10 minutes in order to increase S/N.

3. The selected field should be at higher Galactic latitude to reduce the effects of Galactic extinction; an unextinguished field will yield more than two times as many suitable targets per unit solid angle as the FRESIP field. From the point of view of AGN monitoring, more suitable fields are available in the FRESIP continuous viewing zone.

We note that in the background-limited regime, the highest throughput is attained by the image by matching the Airy disk to the pixel size. The full-width at zero intensity of the Airy disk is

$$\theta_A(\text{radians}) = \frac{2.44\lambda}{D},$$

where λ is the wavelength and D is the diameter of the primary mirror. The angular size of a pixel of size d for focal length F is $\theta_{\mathbf{pixel}} = d/F$. To first approximation, the Airy disk should cover at least two pixels, i.e.,

$$\theta_A \geq 2\theta_{\mathbf{pixel}}$$

which can then be rewritten as a restriction on the system focal ratio

$$f = \frac{F}{D} \geq \frac{d}{1.22\lambda}.$$

Selection of the pixel size is thus of great importance. We believe that a more realistic assumption about the pixel size is $15\,\mu$m rather than $24\,\mu$m. Optimal pixel sizes are basically a trade-off between the difficulty of fabricating small pixels on the one hand and the difficulty of producing high-quality large-format chips on the other. Our perception is, that for large-format chips, pixel sizes $15\,\mu$m and smaller are most likely to be available commercially over the next several years. Thus, for an optical diffraction-limited system with $d = 15\,\mu$m and $\lambda \approx 0.5\,\mu$m, we have $f \gtrsim 25$! Obviously such a long focal length leads to an optical system more complicated than is being considered at the present time. Some simple considerations indicate that we can meet the performance criteria in §3.2 with a smaller telescope ($D \approx 0.3$ m) which has a wide field of view and is capable of fitting into a 2-m shroud. A wide-field telescope may require a refractive corrector, and this may in turn lead to reduction of the bandpass. A more detailed optical design needs to be carried out before any further assessment can be made.

5. CONCLUSIONS

Detailed monitoring of AGNs with FRESIP can provide well-sampled light curves for a large number of AGNs. Such data are *completely unprecedented* in this field, and will provide powerful new constraints on the origin of the UV/optical continuum in AGNs. The FRESIP baseline design will allow 1% photometry on sources brighter than $V \approx 19.6\,\mathrm{mag}$, and we estimate that over 300 sources can be studied. We point out that digitization effects will have a significant negative impact on the faint limit and the number of detectable sources will decrease dramatically if a fixed gain setting (estimated to be nominally $25\,e^-$ per ADU) is used for all read-outs.

We note that the primary limitation to studying AGNs is background (sky and read-out noise) rather than source photon statistics, and thus better results can be achieved by increasing the source/background contrast with a focused telescope and by longer integrations. While we believe that it may be possible to achieve the AGN-monitoring science goals with a more compact and much less expensive telescope, the proposed FRESIP satellite affords an excellent opportunity to attain the required data at essentially zero cost as a secondary goal of a more complex mission.

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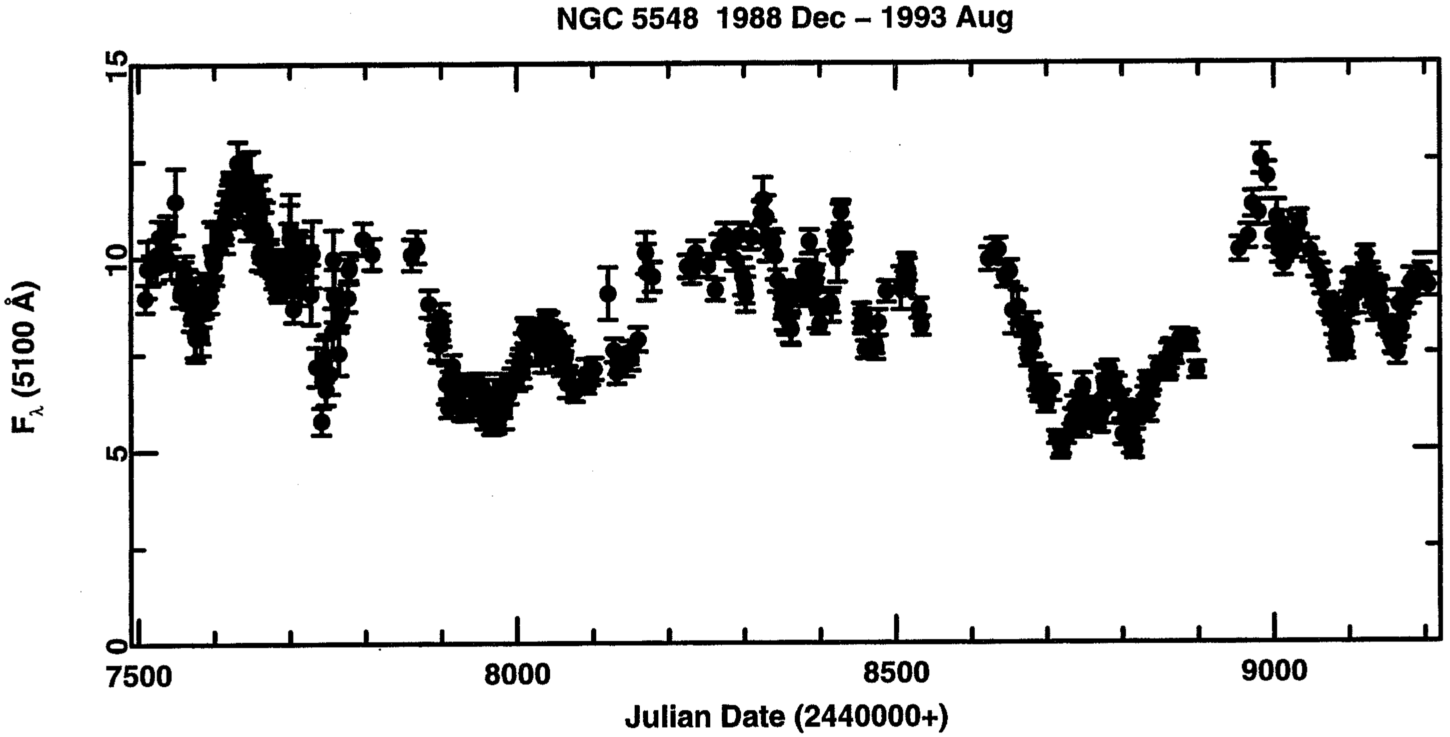
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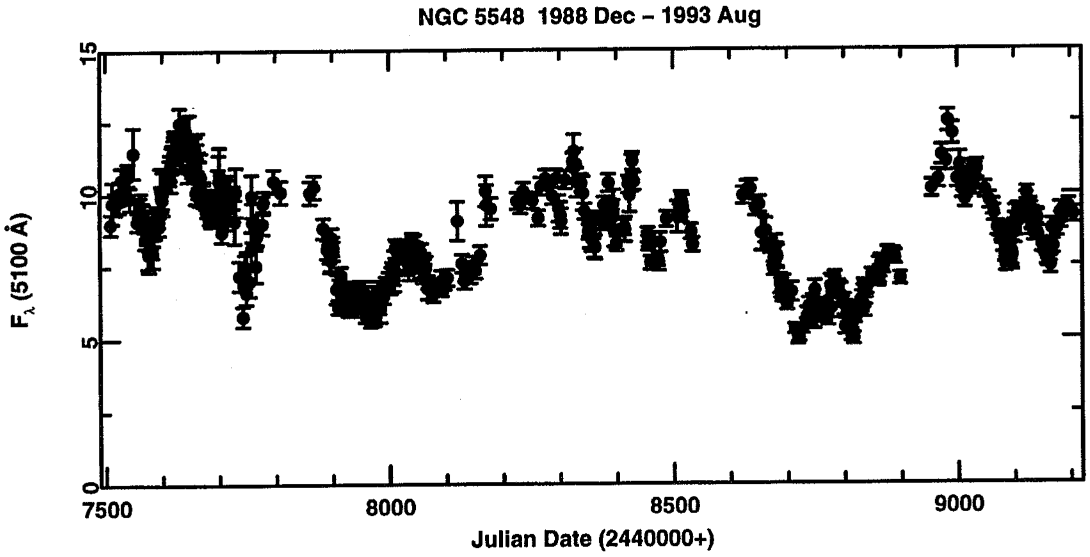
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13. ABSTRACT *(Maximum 200 words)*

The FRESIP project (FRequency of Earth-Sized Inner Planets) is currently under study at NASA Ames Research Center. The goal of FRESIP is the measurement of the frequency of Earth-sized extra-solar planets in inner orbits via the photometric signature of a transit event. This will be accomplished with a spaceborne telescope/photometer capable of photometric precision of two parts in 100,000 at a magnitude of $m_V = 12.5$. To achieve the maximum scientific value from the FRESIP mission, an astrophysical science workshop was held at the SETI Institute in Mountain View, California, November 11–12, 1993. Workshop participants were invited as experts in their field of astrophysical research and discussed the astrophysical science that can be achieved within the context of the FRESIP mission. While the primary purpose of FRESIP is the discovery of Earth-sized inner planets, the workshop participants came up with many additional scientific objectives that are unique to the FRESIP platform, yet require no significant changes to the FRESIP planetary detection mission design. These objectives fall into three broad categories, solar and stellar physics, stellar variability, and extragalactic objects. The types of research which can be conducted in these areas are discussed in detail in the articles which comprise these proceedings.

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