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ASTEROSEISMOLOGY: THE IMPACT OF SOLAR SPACE OBSERVATIONS

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ABSTRACT Observations from space relevant to solar global properties (oscillations, magnetic activity, *etc.*) are helpful both scientifically and technically in preparing for stellar observations. This paper summarizes the results from the main previous experiments (ACRIM, SOUP, and IPHIR), and also give an initial technical report from the SXT instrument on board *Yohkoh*, launched in August 1991. The solar observations to date demonstrate the existence of several mechanisms for low–level variability: spots, faculae, the photospheric network, granulation, and p–mode oscillations. The observations of oscillations have been particularly helpful in setting limits on solar interior rotation. In addition to the solar processes, stars of other types may have different mechanisms of variability. These may include the analogues of coronal holes or solar flares, modes of oscillation not detected in the Sun, collisions with small bodies, duplicity, and probably mechanisms not invented yet but related in interesting ways to stellar convection and magnetism.

INTRODUCTION

Observations from space relevant in any direct way to our knowledge of the solar interior have been few in number, even given the three–decade span of space research and the relative simplicity of some of the basic observations. This paper summarizes the main experiments of the past, emphasizing optical observations bearing on irradiance variability and helioseismology. The data have shown the existence of low–level irradiance variability on all time scales sampled, especially including the p–mode frequency range of a few mHz. These "Sun as a star" observations encourage us very strongly to obtain comparable stellar observations. The fundamental limit of photon arrival statistics does not pose a problem for large numbers of stars of all spectral types, and there appears to be no real limitation imposed by the instrumentation.

The success of these observations illustrates a general point. Traditionally we use observations from space (*e.g.*, in X–ray astronomy) to avoid atmospheric extinction and thus to open a new wavelength ranges for astrophysics. We can also use space to bypass atmospheric seeing effects, for example to improve angular resolution and therefore sensitivity. The experiments described below have made orders–of–magnitude improvements in a different direction, namely in photometric precision, as a result of their deployment in space. These advantages largely remain to be exploited in the stellar domain.

The main contributions have come from the three experiments (ACRIM, SOUP, and IPHIR) described in the next section. The *Yohkoh* spacecraft, launched in August, 1991, is currently returning relevant data, and we give below an assessment of the data quality. Finally, the first sophisticated observations intentionally emphasizing solar global properties will come with the launch of SOHO, and all of the results described here should probably be regarded as precursors to these data.

ACRIM, SOUP, AND IPHIR

These three experiments (see Table I for interpretation of the acronyms) were all launched within the decade of the 1980's. Briefly, ACRIM provided the first credible broad–band observations of solar luminosity variability; SOUP provided the first solar optical imaging observations with good cadence and image stability; and IPHIR provided definitive observations of the solar low–degree p–modes. We note that the total irradiance measurements from *Nimbus–7* preceded those of ACRIM by more than a year and continue to the present, and that NASA has agreed to re–fly ACRIM or otherwise maintain a continuous monitoring of the total solar irradiance. The *Stratoscope* images should also be mentioned here, since these images, with excellent resolution, were obtained from a solar telescope in space (*e.g.* Danielson, 1961). Each experiment made remarkable contributions. In some cases the advances have been duplicated or extended with ground–based data, but the message of their success is clear enough to encourage us towards comparable stellar observations.

TABLE I Solar Space Experiments

Experiment	Full Name	Spacecraft	Time Range
ACRIM	Active Cavity Radiometer Irradiance Monitor	*Solar Maximum Mission*	1980–89
SOUP	Solar Optical Universal Polarimeter	*Spacelab*	1986
IPHIR	InterPlanetary Helioseismology by IRradiance measurements	*Phobos*	1988–89
SXT	Solar X–ray Telescope	*Yohkoh*	1991–??

The above experiments have revealed several types of variability of the solar luminosity. A "frequency domain" view gives a summary of the mechanisms that have been identified to date, as listed in Table II (for more complete reviews, see Hudson, 1988, or Fröhlich *et al.*, 1991). several broad–band noise components modeled as power–law spectral distributions; g–modes; p–modes, and a high–frequency white noise component. The observational identification of the mechanisms for solar variability began with the ACRIM experiment, launched in 1980 and continuing until 1989. From ACRIM we quickly learned that sunspots

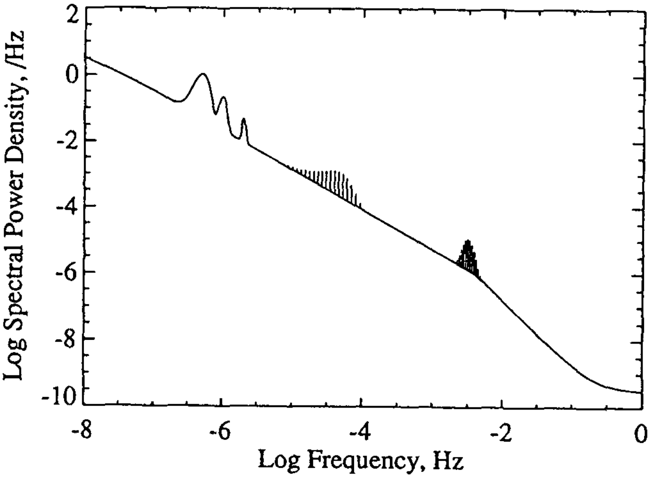

FIGURE I Sketch of the overall power spectrum of a star, modeled on the solar observations. The features represent line and continuum contributions as listed in Table II.

decrease the solar luminous output, essentially in the measure expected from their projected areas (Willson *et al.*, 1981). Subsequently the p–mode oscillations were found to make tiny variations in the solar luminosity (Woodard and Hudson, 1983). These were the easy effects to identify. The effects associated with faculae are much more complicated and still do not have a complete resolution. The irradiance perturbations come from facular elements at the smallest size scales, and yet they are closely associated with the relatively long time scale of the solar–cycle modulation, or even longer time scales (Foukal and Lean, 1990). The longer time scales have direct significance for stellar observations, since the Wilson program has revealed the existence of photometric cycles on solar–type stars with time scales comparable to the solar time scale of 11 years (*e.g.* Baliunas, 1985).

At frequencies above the 3 mHz vicinity of the p–modes, the solar variability spectrum is not known well. The power spectra of ACRIM data in Figure II (Fisher *et al.*, 1992) show that the spectrum falls off rapidly above the p–mode band. These spectra come from the incoherent sum of many individual orbits over the period from July 15 to October 16, 1989, during a period of relatively high solar activity. The right panel of Figure II shows the result of subtracting a best–fit constant term (white noise) from the raw spectrum of the left panel. The ACRIM white noise presumably is the instrumental noise floor, not a separate component of solar variability.

The definitive helioseismic observations in integrated sunlight were then carried out by the IPHIR photometers on board *Phobos* (Toutain and Fröhlich, 1992). These simple measurements are an excellent precursor to asteroseismology. The IPHIR data analysis overcame long–term detector degradation and demonstrated that this would not preclude obtaining the high frequency resolu-

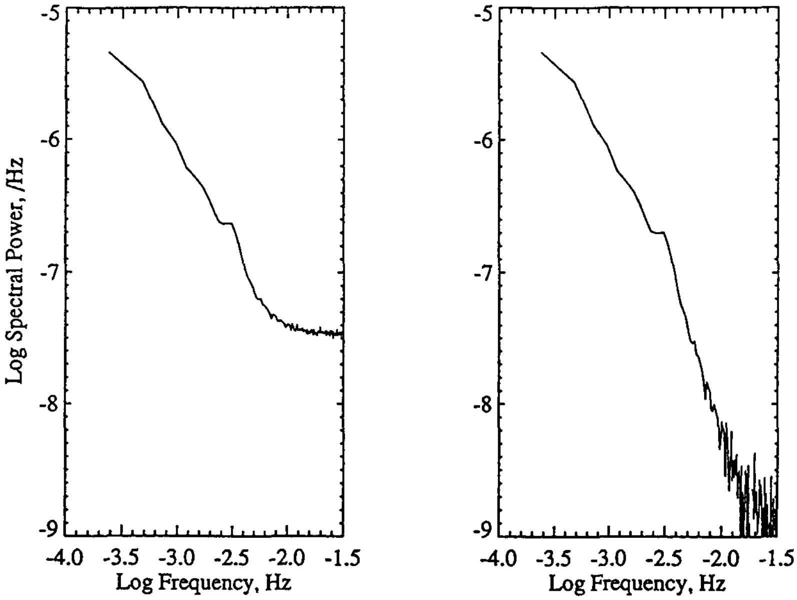

FIGURE II Low–resolution power spectra from the ACRIM experiment on board the *Solar Maximum Mission* — left, a sum of raw spectra; right, the sum with a fit to the white noise at high frequencies subtracted.

tion enabled by long, continuous time series.

TABLE II Variability of Solar Luminosity

Mechanism	Time scale	Amplitude
Oscillations	5 min	few parts per million
Granulation	tens of min	tens of parts per million
Sunspots	few days	< 0.2% peak–to–peak
Faculae	tens of days	< 0.1% peak–to–peak
Solar cycle	11 years	~0.1% peak–to–peak
Trend	tens of years	~0.1% peak–to–peak

The SOUP observations from *Spacelab*, while restricted to a narrow field of view and the use of film as a detector, demonstrated excellent stability. There were significant results in "solar astrometry," feature tracking, in spite of the limited amounts of data, and these results are instrumental in the newly developing view of the nature of solar convection (Title *et al.*, 1989).

YOHKOH AND SXT

Yohkoh ("Sunshine" in Japanese) is at present the main spacecraft with an experiment relevant to the general topics of stellar activity and global properties (Ogawara *et al.*, 1992). This is SXT, a soft X–ray telescope that will be discussed briefly here (see, *e.g.*, Tsuneta *et al.*, 1991, for fuller details) . The general properties of SXT appear in Table III. The X–ray imager itself consists of a grazing–incidence telescope with a set of broad–band filters for spectral analysis in the vicinity of 1 keV photon energy. This telescope forms images on a 1024 × 1024 pixel CCD with pixel subtense 2.46 arcsec. In addition to the X–ray imager, SXT contains a concentric 5–cm lens that forms optical images on the same CCD, principally for alignment of the X–ray images relative to solar optical features.

TABLE III The SXT aspect camera on board *Yohkoh*

Orbital inclination	31°
Orbital period	~97 min
Focal Length	1538.4 mm
Aperture	50 mm
Exposure times	0.1 – 1 sec
Pixel size	2.46 arcsec (1024 × 1024 CCD)
Wavelength	Two broad-band filters
Sampling	A few 512 × 512 images per day

The data from this aspect camera are the relevant item here, since they are providing the first long–term optical observations of the Sun from space with a photometrically stable imaging detector. The typical observational sequence has been to obtain one 2 × 2 image, *i.e.* an image with 4.92 arcsec pixels, approximately 10–15 times per day. Additional optical images for special purposes are also taken from time to time, for example at a high cadence in searching for white–light flare emission during the occurrence of a flare, or by special programming.

The data in Figure III show some results from a special set of observations carried out on Feb. 25, 1992, to test the photometric stability of the *Yohkoh* CCD camera. The observations consisted of a continuous sequence of 256 × 256 images of the whole Sun (9.84 arcsec pixels) taken through a 140 Å filter with a central wavelength of 4580 Å. The *Yohkoh* telemetry system permits one such image to be taken every 32 sec, but introduces gaps as can be seen in the time series. Nevertheless, these data can be analyzed to illustrate the CCD stability. In the initial data reduction, we subtracted the dark–current background but did not attempt to "flat–field" the images. The sum of the data from the central 64 × 64 pixels, as a fraction of the total signal, is shown in Figure III. The rms amplitude of this time series is 2.55×10^{-4}, approximately consistent with the amplitude expected from the ACRIM broad–band data. At this frequency, the ACRIM fluctuations are modulated by the level of solar activity. Much of this variation is solar in origin. There is also a presently–unknown contribution from

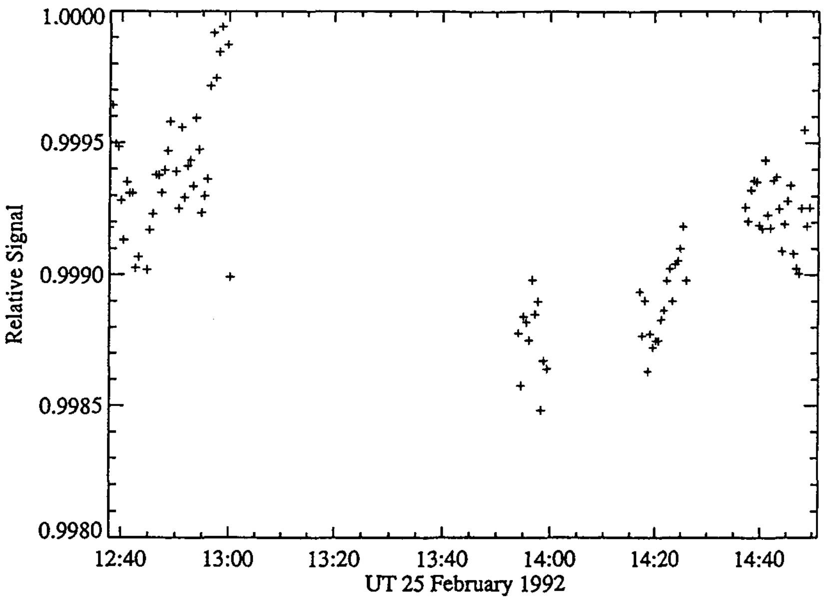

FIGURE III Time series of data from whole–Sun images obtained with the CCD detector of the SXT instrument on board *Yohkoh*; the minimum sample spacing is about 32 sec and the time series contains 97 images.

flat–field imperfections modulated by the spacecraft pointing jitter (a total range of approximately 10 arcsec in the present data set). We thus conclude that on this time scale (about two hours total), and by inference on shorter time scales, the *Yohkoh* CCD exhibits adequate stability for asteroseismology investigations.

The *Yohkoh* data, in the test time series shown in Fig. II, achieve a high–frequency noise level consistent with the statistics expected for the total number of photons detected ($\sim 10^{11}$) during the two–hour duration.

CONCLUSIONS: THE IMPACT OF SOLAR SPACE EXPERIMENTS

This paper discusses the current solar observations as a guide towards stellar observations related to global properties, and in particular to asteroseismology. We summarize first the main scientific conclusions that have been drawn from the existing data:

- There are several mechanisms of low–level variability of the solar luminosity, mostly broad–band in character.
- The solar p–modes are easily visible as small perturbations of the solar luminosity (*i.e.*, using integrated sunlight as a source).
- There is a solar–cycle variation of p–mode frequencies.

- The frequency splittings of the low–degree p–modes establish that the solar core is not rotating extremely rapidly.

The lessons that should be drawn from these successful solar observations might be summarized as follows:

- Relatively simple instrumentation can produce significant results.
- Observations from space are superior to ground–based observations because they avoid fluctuations in brightness and image shape from seeing effects, and because they allow long, interrupted time series.
- Optical observations are the most important for stellar work, since the photon–statistics limit can be approached. The solar observations suggest that this limit is achievable also with CCD detectors.

These results are a promising beginning and there is no reason to suppose, on the basis of the present solar observations, that a photometric approach to asteroseismology will not be feasible. On the other other hand, there are mechanisms of stellar variability not presently detected on the Sun, and these are potential sources of "noise." Some of these may be oscillatory, and others random in nature. Before the analysis of the ACRIM data we had hoped to detect solar flares in the total solar irradiance values, for example, but this search has not yet been successful (*e.g.* Hudson and Willson, 1985). Additional possible mechanisms for stellar variability include duplicity, occultation by dark external bodies, collisions with small bodies, non–solar modes of oscillation, the stellar analogs of coronal holes, and probably many others.

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