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The Solar Mass Ejection Imager

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Abstract. We are designing a Solar Mass Ejection Imager (SMEI) capable of observing Thomson-scattered signals from heliospheric density features from a spacecraft situated near 1 AU. The imager is designed to trace these features, which include coronal mass ejections, corotating structures and shock waves, to elongations greater than 90° from the Sun. The instrument may be regarded as a progeny of the heliospheric imaging capability shown possible by the zodiacal light photometers of the HELIOS spacecraft. The instrument we are designing would make more effective use of in situ solar wind data from spacecraft in the vicinity of the imager by extending their observations to the surrounding environment. An imager at Earth could allow up to three days warning of the arrival of a mass ejection from the Sun. In combination with similar instruments in deep space SMEI can be used for stereoscopic imaging of heliospheric features.

1 Introduction

The Solar Mass Ejection Imager (SMEI) is designed to map large-scale variations in heliospheric electron densities from Earth orbit in Thomson-scattered light. A portion of an early prototype version of an instrument (baffle, optics, and some of the data analysis schemes) has been constructed for preliminary study (Jackson et al., 1991). In section 2 of this review, we give the signal levels expected from various heliospheric features as derived from the HELIOS spacecraft data. The third section describes how the instrument is expected to operate. The fourth section describes the SMEI instrument configuration for Earth orbit. A variety of background sources of light that might interfere with the instrument are given in the last sections of the review followed by a brief conclusion.

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TABLE 1 Signal Levels Expected at 1 AU

Feature	Elongation (degrees)	Signal Intensity (S10)	Signal Duration (days)
Bright CME	60	2	1.5
	90	1	1.5
Bright streamer	60	2	1
	90	1	1
Bright shock	90	0.5-1	≤0.5
Major unidentified *in situ* fluctuation	60	3	2
	90	2	2
Comet shock	20	3-10	-

2 Signal Levels and Numbers of Photons

Because the faint coronal features we wish to detect are much less bright than the Sun, the SMEI must be designed carefully to eliminate stray light. Table 1 estimates the signal levels expected for various phenomena at 1 AU.

The brightnesses of coronal mass ejections (CMEs)(Fig. 1) and streamers were derived from features traced outward from the Naval Research Laboratory SOLWIND coronagraph (Sheeley et al., 1980) and the High Altitude Observatory SMM coronagraph (MacQueen et al., 1980) and from features observed with the HELIOS photometers (Leinert et al., 1981) by Richter et al. (1982) and others (Jackson, 1985; Jackson and Leinert, 1985; Webb and Jackson, 1990; Jackson, 1991; Webb et al. 1995). Shock brightnesses were estimated from the in situ plasma density enhancements behind shocks observed from the HELIOS spacecraft and assumed to be viewed at 60° and 90° elongations - angular distances from the Sun-spacecraft line (Jackson, 1986). The comet shock estimates are from Jackson and Benensohn (1990). Signal levels in Table 1 are given in terms of "S10 units" which are equivalent to the flux of a single tenth mag-

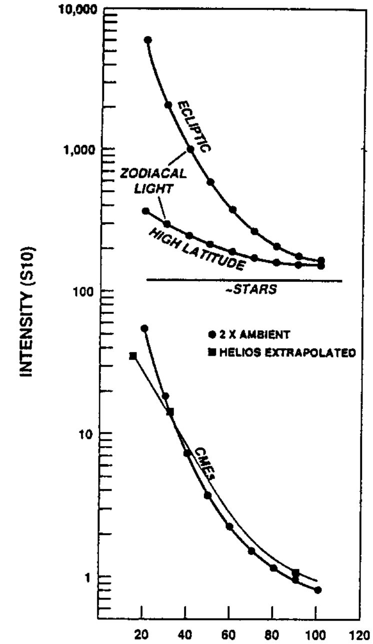

Fig. 1. The brightness of various signals that will be observed by the imager versus elongation at 1 AU.

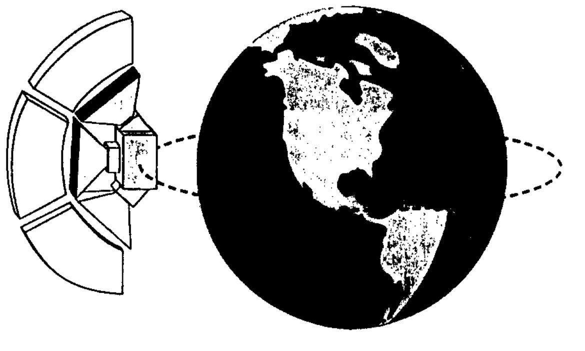

Fig. 2. SMEI in a typical equatorial orbit. The spacecraft orbit is circular at 800 km above the surface of the Earth.

nitude star per square degree of sky.

The Thomson-scattered coronal light must be detected in the presence of background diffuse light from many sources: scattered light from bright sources such as the Sun, Moon, or Earth; the zodiacal light; and the stars, either individually as bright point sources or collectively as a contribution to the diffuse sky brightness. Figure 1 is a plot of estimates of the brightness contributions from these signals to be observed from an Earth-orbiting SMEI at different elongations from the Sun. The Sun is the equivalent of 5×10^{14} S10 units. The ultimate limit of diffuse-light sensitivity should be set by photon counting statistics; this limit depends upon the optics and scanning configuration, spectral bandpass, and total detector efficiency. The total detected photon count N can be approximated as in Jackson et al. (1989) by

$$\log N = 6.75 - 0.4m_V + \log A + \log(\Delta t), \qquad (1)$$

The background sky brightness varies roughly over the range 100-6000 S10 units between the darkest sky and the ecliptic plane at solar elongations $\approx 20°$ .If we assume that A = 2 cm^2 is the size of the one by two centimeter rectangular aperture as in the design for the proposed SMEI (JHU/APL, 1992) and Δt = 4 s, then from equation (1) we obtain 4500 photons available per given 1 square degree of sky for a brightness of 1.0 S10 unit ($m_V = 10$). Detector bandpasses and other instrumental factors further decrease the number of photons which can be detected.

For a slowly rotating low-Earth orbiter with many signal photons present in each pixel, it becomes possible to use a CCD detector to integrate the incoming photons. This permits a sufficient signal to build up above a statistical noise readout level. The proposed SMEI instrument has been developed around the possibility of using a Thomson TH7863 CCD chip. Current design efforts suggest that it may be feasible to use an even larger-format CCD, such as the TH7899, if it can be shown to have a similar low pixel to pixel and subpixel variation response. The ultimate spatial resolution is determined by the smallest sky resolution element in which heliospheric signals can be detected above the far brighter zodiacal light background. The heliospheric signal is detected provided the total noise for this sky resolution element is less than the signal.

3 Instrument operation

We expect that the SMEI instrument, operating in conjunction with others, would allow an accurate forecast of solar mass ejections heading toward Earth. The changing sky brightness measured from SMEI can be expected to be used tomographically to determine heliospheric structure shapes in three-dimensions prior to their arrival by assuming a radially expanding solar wind. With additional instruments available in deep space true stereoscopic imaging would be possible. These analyses, in conjunction with solar observations of flare brightenings, disappearing filaments, coronal hole locations, magnetic field observations, and additional heliospheric observations, such as velocity interplanetary scintillation measurements, can be expected to sharpen the instrument forecast capability.

4 Orbital Configuration and SMEI Layout

One of the simplest and most economical orbits for the SMEI would be equatorial at 800 km above the Earth. A circular polar orbit at the same height should also be adequate. From such an orbit, the brightest objects to be

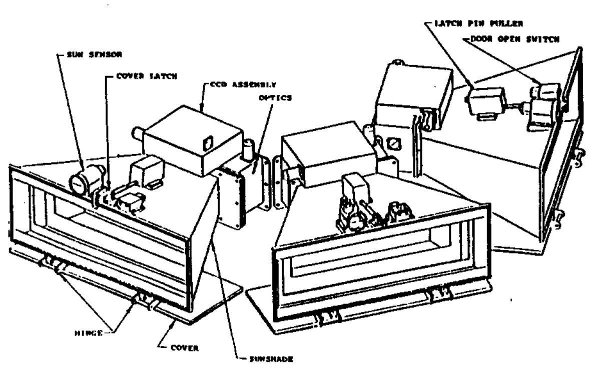

Fig. 3. Layout of the proposed SMEI.

eliminated from the SMEI view are the Sun, the Earth, and the Moon. From low-Earth orbit the Earth can be nearly as bright as the Sun and covers nearly half of the celestial sphere. The source of this background light is controlled by having SMEI point away from Earth. Figure 2 gives a schematic of the SMEI instrumentation in a typical 800 km equatorial orbit. Figure 3 gives a schematic layout of the proposed SMEI instrument.

5 Background Signals

Light from the sky such as zodiacal light, the Milky Way and other stars is generally brighter than the variable Thomson-scattered signal we wish to detect. These contributions must be removed from the data unless they are constant from orbit to orbit. From the HELIOS orbit, the zodiacal light appears to be unchanging in time and smoothly varying spatially to near the desired detection brightness threshold for SMEI. Knowing the orientation of each data frame in the sky permits removal of this source of background light, by means of a lookup table, a mathematical algorithm, or by assuming an unchanged value from an average of previous orbits. Stars can be dealt with in a similar fashion. However, because these are spatially limited sources of light, the location and orientation of each sky resolution element must be known to high precision to reduce this background contribution.

6 Zodiacal Light and the Gegenschein

The Zodiacal Light brightness varies with ecliptic latitude (Figure 1). In principle, this light should present no problem for SMEI as long as the zodiacal light intensity does not saturate the imager or the statistical fluctuations of its signal do not exceed the faint Thomson scattering signal we wish to detect.

We are fortunate that the HELIOS spacecraft has provided a working model for the SMEI. A hypothetical small percent variation in the zodiacal cloud at the spatial or temporal scales of features we wish to detect might mask the signals of interplanetary features. The HELIOS data placed an upper limit on these variations of approximately 1 S10 unit. We presume that at the spatial and temporal scales of heliospheric brightness changes, the zodiacal cloud remains smooth and temporally non-varying even below this level. Gegenschein light, thought due to backscatter from the zodiacal cloud, is present in the direction opposite the Sun at a level of about 200 S10 units. Early ground-based reports of this light being mottled at the level of 20 S10 units (Hong et al. 1985) have not been confirmed by the HELIOS spacecraft observations.

7 Starlight

Starlight in general is present as discrete sources of light. However, the brightnesses of stars (Figure 1) are comparable to 120 S10 units in all directions (Allen, 1964). There is on average one 8th magnitude star in every square degree. Certain portions of the sky are brighter than others and may present problems for SMEI. These include the Milky Way and other large diffuse objects such as M31 and the large and small Magellanic Clouds. Some imager resolution elements may contain a bright or variable star that overwhelms the Thomson scattering signal at that location in the sky. These will need to be identified and removed from the record on each orbit. If the option is available to transmit all the data to the ground, as is presumed possible from most low-Earth orbiters, then on-board processing of data is not necessary and the instrument electronics becomes simpler. The algorithms needed to analyze the data can be applied once the data are on the ground and, if necessary, can be adjusted to improve their performance.

8 Auroral Light and the Geocorona

Light from aurora on rare occasions has been reported by Shuttle astronauts as high as 1000 km above the surface of the Earth (George Carruthers, private communication, 1991). Jackson et al. (1992) estimate auroral brightness above 800 km and conclude that these emissions could occasionally become greater than 1 S10 unit. If aurorae this bright were to occur over time intervals short relative to successive orbital passes of the spacecraft, they could interfere with the operation of SMEI, but only in the darkest parts of the heliosphere and at very specific positions relative to Earth's geomagnetic equator.

The geocorona has been detected at various wavelengths, but especially in hydrogen Lyman alpha radiation as a glow in the direction towards the Sun (Meier and Mange, 1973). Typical brightnesses of the geocorona in Balmer α emission (6563 Å) are known to be as great as 20

Rayleighs or as bright as ≈2.0 S10 units. The brightness fall-off with height above the surface of the Earth is unlike that of the aurorae in that the geocorona is brightest at heights of >103 km. This emission, if included in the imager bandpass, could contribute a background comparable to the signal photons observed by the SMEI at 90° elongation and greater. However, the geocorona to first order remains approximately constant relative to solar elongation and is brightest towards and to the west of the Sun (Anderson et al. 1987). The relative invariability of the geocorona at a given solar elongation on the time scales of mass ejections implies that this source of brightness should pose no problem for an Earthbased imager, especially if Balmer alpha emission is excluded from the instrument bandpass.

9 Ram Glow and Other Spacecraft-Produced Illumination

Ram glow is a low-level light source which forms a comet-like halo and tail near a spacecraft in low-Earth orbit. The glow is caused by many different sources (Torr, 1988) including a concentration of the ambient gasses which peak in the ram direction, outgassing from the spacecraft, leakage, venting and thruster firings. The amounts of this glow vary from spacecraft to spacecraft. From Space Shuttle measurements at heights below 400 km some of the constituent molecular glows from atmospheric oxygen are significantly above the ≈100 S10 unit zodiacal light background at 90° elongation. If the source of this light were to vary, it could cause significant problems for the imager at these heights. However, with the possible exception of sources on the vehicle such as emissions from other experiments, these sources of light extrapolate to well below the level that could cause a detrimental effect on the imager at the 800 km orbit.

10 Conclusion

Results from the HELIOS spacecraft have demonstrated that the SMEI concept will work, and they give limits on the signal levels necessary for an instrument capable of tracing solar mass ejections, corotating regions and shock waves through the heliosphere from Earth orbit. Although several designs are possible, the SMEI instrument must be deployed above the aurora and molecular glows at an orbital height of 800 km and will operate only when Earth is not included in its field of view. Thus, an Earth-orbiting SMEI viewing away from Earth depends on the slow orbital rotation of the spacecraft to scan the whole sky once every 90 minute orbit. Such an instrument would have the capability of forecasting the arrival at Earth of heliospheric features in real time.

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