Keeping Watch on The Sun

Chris Williams
Student 1607421
HET 610

3rd April 2003

The Sun is far from a dormant ball of gas. Its surface seethes with activity including sunspots, solar flares and prominences, which send plasma arcing many thousands of kilometres above the Sun's surface. An essentially continuous stream of charged particles, called the solar wind, emanates from the Sun at velocities in the order of 300 to 800 kilometres per second [1]. Normal solar activity poses little threat to the Earth because of the protection afforded by Earth's magnetic field and atmosphere. However, from time to time there are massive outbursts when the Sun ejects tremendous amounts ($10^9 - 10^{11}$ tonnes [2]) of hot, ionised gas outward at speeds as high as 1000 kilometres per second. These outbursts are called coronal mass ejections (CME) and are more likely during periods of high sunspot activity (approximately 11 year cycle). CMEs can cause disruption of satellite systems and radio communications on Earth approximately 40 to 50 hours after emission. In extreme cases, such as during an event in March 1989 affecting Quebec's power supply, electricity grids and other ground-based electrical systems can be crippled.

Given the potential disruption to Earth, it is important that advance warning of CME activity is available to allow damage limitation activity to take place. This essay examines a space-based early warning system to be placed at one of the Earth-Sun Lagrange points, and to operate for two solar activity cycles (25 years).

Location

The principle requirements for the spacecraft location are;

- uninterrupted view of the Sun allowing determination of solar activity directed toward Earth,
- uninterrupted communication with Earth,
- on-station orbit requiring minimum manoeuvring fuel.

Earth orbits are excluded by the requirement for continuous solar observation because the satellites must, at some time, pass into the Earth's shadow. While this could be overcome by deploying a complementary fleet of spacecraft, this increases the cost and complexity. Low Earth orbits also decay because of atmospheric drag, necessitating routine operations to readjust the orbit, and increasing the fuel required to hold station. Clearly a heliocentric orbit is required, but placing the spacecraft Sun-ward of the Earth makes the period of its orbit shorter than a year meaning the spacecraft will not hold its position with respect to Earth, and will sometimes be on the far side of the Sun and incommunicado. There are a number of locations in the Earth-Sun system, known as Lagrange points, at which the competing effects of the Sun and Earth's gravitational field interplay to produce dynamically stable points that co-rotate with the Earth's orbit. Figure 1 shows the Lagrange points with their conventional numbering. Point L2 can be eliminated because it is permanently in Earth's shadow. Point L3 cannot communicate with Earth, and can thus be eliminated. Points L4 and L5 could be used, but their point of view is dissimilar from Earth's, requiring more complex analysis to determine if a CME is Earth-bound. The elimination process leaves only L1; 1.5 million kilometres from Earth.

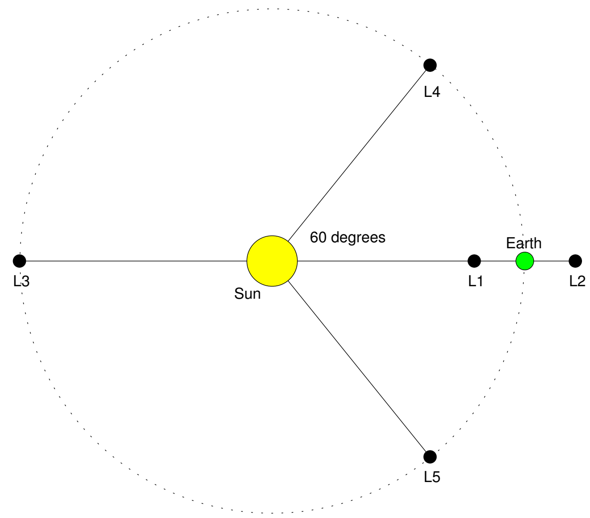

Figure 1: Lagrange Points in Earth-Sun System (not to scale). The L1-Earth distance is approximately 1.5 million kilometres.

Instrumentation

CMEs are characterised by intense activity in the Sun's corona, visible as emissions from energetic ions. Normally the corona is not visible due the intense glow of the Sun's surface, but is visible during a total solar eclipse when the Sun's disc is occulted by the Moon. A coronagraph artificially creates an eclipse using an occulting disc or mirror placed in the light path, and can be used to make corona observations at any time (Figure 2). A CME directed at the spacecraft, and by extension the Earth, will appear as an abnormally bright halo around the occulting disc. CMEs directed elsewhere will be asymmetric with respect to the occulting disc.

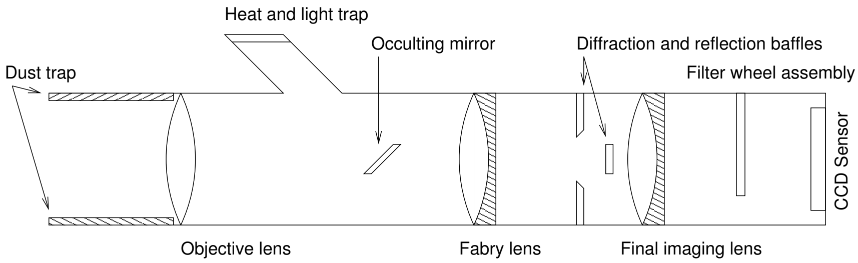

Figure 2: A typical coronagraph. Adapted from [3, pp. 402].

The early-warning coronagraph should meet the following broad requirements;

- a field of view to encompass at least 10 solar radii around the Sun's disc,
- sensitivity at several key emissions wavelengths for CME stimulated emissions,
- cryogenic cooling fluid-free design, and
- exposed optical components able to withstand 25 years of exposure to the solar wind.

The field of view requirement will dictate the key characteristics of the coronagraph optics. It may be necessary for the spacecraft to carry a compound instrument with several complementary fields of view. The coronagraph sensor will consist of a charge-coupled device (CCD) supplemented by filters to pick out the emissions or absorptions (e.g.Fe XIV, Ca XV, Na I D, and Fe X) of interest from the corona. Heat build up within the coronagraph, its optical elements, occulting mechanism, and CCD sensor must be tightly controlled, but cannot rely on liquid helium or similar cryogenic coolants, which could not be carried in sufficient quantity for the planned mission life. Solid-state (Peltier) cooling systems are power hungry devices, so passive radiator elements are the likely choice for the CCD cooling. Exposed surfaces of the instrument will be subject to constant bombardment by charged solar wind particles, and must be sufficiently resistant to this in order to last the mission lifetime.

Launch and Spacecraft Systems

Given the single task nature of the proposed spacecraft, and the size of more complex craft in L1 orbit, such as SOHO, it seems reasonable to expect a relatively small launch vehicle could be used. SOHO made use of an Atlas IIAS (liquid fuel with solid boosters) launch stage and relightable Centaur stage to place a 610 kilogramme payload on station around L1 [4]. The extended life of the proposed spacecraft will necessitate carrying more weight than SOHO in on-station fuel reserves, but this can be offset by instrumentation weight savings. The nature of the L1 Lagrange point is such that a spacecraft cannot be precisely positioned there and expected to stay. The L1 point can, however, be orbited in a fashion called a halo orbit. The spacecraft moves around the L1 point over time, but the interplay of the Sun and Earth gravitational fields means that little fuel is required to keep station. Careful design of the halo orbit also serves to keep the spacecraft off the Earth-Sun line so that its transmissions are not swamped by solar emission. Insertion into an L1 halo orbit is a complex task requiring the spacecraft to leave the ecliptic. Such manoeuvres have, however, already been used for orbital insertion of the SOHO spacecraft [5] and should not pose a substantial problem.

Two spacecraft systems will be required to hold station; a reaction wheel arrangement to permit accurate pointing of the spacecraft instruments, and a hydrazine thruster system to make orbit corrections and to despin the reaction wheels as required. Spin stabilisation of the spacecraft is not suitable because of added complexity required to counter-spin communications antennae, instruments, and manoeuvring thrusters. While the spacecraft could function using only hydrazine thrusters (as does SOHO) the lifetime would necessitate larger, exhaustible fuel reserves. Reaction wheels are electrically powered and therefore can run indefinitely, barring mechanical failure, assuming sufficient electrical capacity is carried. Optionally, the propulsion system can carry reserves capable of removing the spacecraft from the L1 region at the end of life.

The spacecraft will spend its in-service lifetime with a single side constantly facing the Sun. Thermal control systems must therefore be designed to handle the disparity between light and dark sides of the craft. Techniques such as periodically rotating the craft to even heating over the surface are not possible. Heat reflective shielding on forward surfaces, coupled with heat pump systems, should be able to keep spacecraft systems within operating tolerances. The coronagraph CCD camera is heat sensitive and must be efficiently cooled to minimise image degradation.

The twenty-five year desired spacecraft life dictates a power source that does not require a large fuel reserve. Given the constant exposure to sunlight, solar cells seem the obvious choice. Solar cells do, however, degrade with time and micrometeorite impact, as was the case with ten year old solar panels retrieved from the Mir station [6]. Solar arrays would therefore have to account for this deterioration with excess capacity at launch time. The solar arrays would not need to be steerable as the spacecraft will keep a Sun-ward attitude at all times during on-station operation. During the launch, solar panel deployment, and possibly during Earth-L1 transfer when panels are not favourably oriented, the craft will require short-term battery power. An alternative to solar power would be radio-isotope thermal generators, but these are politically unpopular due to potential launch mishaps and consequently only used where solar power is infeasible.

Communication between the spacecraft and Earth will require the installation of a high-gain dish antenna on the Earth-ward side of the spacecraft. This antenna should be supplemented with at least one, less complex low-gain antenna as a failsafe. The spacecraft transmitters and receivers should be designed to survive the likely radiation load and, given the spacecraft mission lifetime, should include redundant circuits for lower reliability components. Data transmission rates should enable relay of images and spacecraft telemetry to Earth on a short time frame to permit timely analysis and warning of CME events. On board data storage is required in the event that Earth receiving stations are not available, or the low-gain, low data rate antenna is in use.

Conclusion

The design of an early-warning spacecraft to monitor the Sun's potentially detrimental emissions has been discussed. The spacecraft's primary instrument is a coronagraph tuned to detect emissions typical of coronal mass ejections. Imagery will be collected using a passively cooled CCD and stored locally pending transmission to Earth. The spacecraft will spend its twenty-five year operational life in a halo orbit of the L1 Lagrange point, approximately 1.5 million kilometres Sun-ward of Earth. Solar cells will provide the spacecraft's primary electrical power source, but a battery will provide short-term power to run spacecraft systems, deploy solar panels, and as needed during orbital insertion. Electrically powered reaction wheels will be used to control spacecraft attitude, while small rockets are used for occasional on-station orbital adjustments. Communication with Earth will be via a high gain antenna at high data rates, with a low-gain antenna as a lower speed, failsafe backup. Transmitter and receiver components with lower reliability will be backed up with redundant systems.

References

[1] D. H. Hathaway. The solar wind. Internet `http://science.msfc.nasa.gov/ssl/pad/solar/sun_wind.htm`, January 2003.

[2] NASA/ESA. LASCO coronal mass ejections lists. Internet `http://lasco-www.nrl.navy.mil/cmelist.html`, January 2003.

[3] C.R. Kitchin. *Astrophysical Techniques*. Institute of Physics Publishing, 3rd edition, 1998.

[4] NASA and ESA. The solar and heliospheric observatory. Internet `http://sohowww.nascom.nasa.gov/`.

[5] F. C. Vandenbussche and P. Temporelli. SOHO - the trip to the L1 halo orbit. *ESA Bulletin*, (88), November 1996.

[6] J. C. Mandeville and M. Bariteau. Cosmic dust and micro-debris measurements on the MIR space station. *Advances in Space Research*, 28:1317–1324, 2001.