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Reprint

Prospects for Observing Space Debris With Solar Coronagraphs

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Solar coronagraphs appear to offer significant advantages over conventional telescopes for observing space debris of small size. By utilizing the albedo-independent, high sensitivity of coronagraphs for detecting particulates angularly close to the sun, it is shown that observed photon fluxes will be many orders of magnitude larger than for observations based on diffuse reflection (backscattering). This may result in signal-to-noise ratios sufficiently large to detect particles an order of magnitude smaller than can be detected via backscattered solar radiation using a conventional telescope with the same aperture as the coronagraph.

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signal for this nighttime observation is $38 \text{ electrons/s/pixel}$ with noise equal to $[\text{background}]^{1/2}$ plus read-out noise. For very short exposures the noise will be dominated by read-out noise.

Figure 1 compares the signal/noise ratios for both of the described instruments. The 0.001-s exposure limits the length of the debris tracks to ≤ 3 pixels in length. For these very short tracks, it is reasonable to adopt as a detection limit a per-pixel S/N ratio equal to 1. In this case the coronagraph should, in principle, be able to detect debris down to about 0.1 cm in diameter—a factor of about 20 smaller than the conventional telescope's nighttime limit for an identical exposure. The detection limits of both instruments, however, can be lowered by increasing the exposure times to acquire longer tracks. The per-pixel S/N ratio is then somewhat decreased by the increased background signal, although the debris signal, now being deposited on the resulting larger number of pixels, can be used to advantage through application of appropriate extraction algorithms. If, for example, the coronagraph exposure is pushed close to the 0.1 s saturation limit (giving a debris track 100 times longer), the per-pixel S/N detection limit will be reduced by a factor $100^{1/2}$, to 0.1, corresponding to debris diameter 0.05 cm. The same procedure works even better with the nighttime observation, where saturation by the background is not a problem. In this case the stare-mode exposure could be increased even to equal the detector field-of-view crossing time (≈ 1 s). This would provide a debris track 1000 times longer, reducing the per-pixel S/N limit to 0.03. The corresponding limit on debris diameter would be 0.5 cm. Of course, with the low background signal, there is nothing to prevent the conventional telescope from realizing further improvements by employing quasi-tracking and even longer exposures. In general, the acquisition of debris tracks of intermediate length, in stare-mode operation, is important as a means of measuring debris angular velocity.

If we make the debris observations from space, we find that both techniques benefit from the absence of sky background. In the following, we compare two instruments of 20-cm aperture, both observing in the 5500-7500 Å range with the same CCD detector as assumed above for the ground-based conventional telescope. The saturating exposure for the coronagraph, assuming a deep CCD well of approximately 3×10^5 electrons/pixel, is again 0.1 s, which is determined by the background corona and instrumentally-scattered light. The conventional telescope observing debris via backscattering will encounter no background at all, so that the only noise will be the CCD read-out noise. The assumed debris target is at distance of 100 km and moving at 1 km/s across the line of sight (1-arcsec pixel crossing time 4.8×10^{-4} s). Figure 2 shows the expected S/N ratios for 0.01-s and 0.1-s coronagraph exposures, and, for the conventional telescope, an exposure of any duration greater than the pixel crossing time. The coronagraph's detection limit, based on $S/N=1$ in each pixel, is 0.03 cm diameter for the 0.01-s exposure, or a factor of 100 smaller than the limit for the backscattering observation. However, this advantage is greatly reduced if the limits are based on track detection instead of per-pixel detection. The 0.1-sec coronagraph exposure provides a debris track ≤ 200 pixels, so that, assuming track detection, the per-pixel S/N ratio can be set a factor $200^{1/2}$ lower; this would result in a limit of 0.02 cm diameter for the observed debris. The backscattering observation, on the other hand, suffering no penalty for increased exposure time, is able to acquire a full 2000-pixel track at no expense of noise. The per-pixel S/N ratio can therefore be set at 0.001, corresponding to a debris diameter 0.1 cm—a factor of 5 larger than the coronagraphic limit.

Several small-aperture coronagraphs have already been flown in space. Although the objectives of these experiments were to observe the solar corona, and the instruments optimized for this application, a number of debris detections were made. Schuerman et al. (1977) reported

numerous such detections, the majority of which were particles in the vicinity of the Skylab module. Additional reports (unpublished) have noted debris detections by the Solar Maximum Mission coronagraph experiment. A somewhat larger aperture (10-cm) space coronagraph is currently under development by the Smithsonian Astrophysical Observatory and the National Solar Observatory, as part of the Space Weather and Terrestrial Hazards (SWATH) mission. The latter experiment, initiated in 1993 under funding by the Ballistic Missile Defense Organization and administered through the Phillips Laboratory, includes several instruments for simultaneous visible light and x-ray/EUV observations of the corona. The SWATH coronagraph, with a sensitivity nearly two orders of magnitude greater than previous space coronagraphs, will be operated in a mode designed to detect orbital debris.

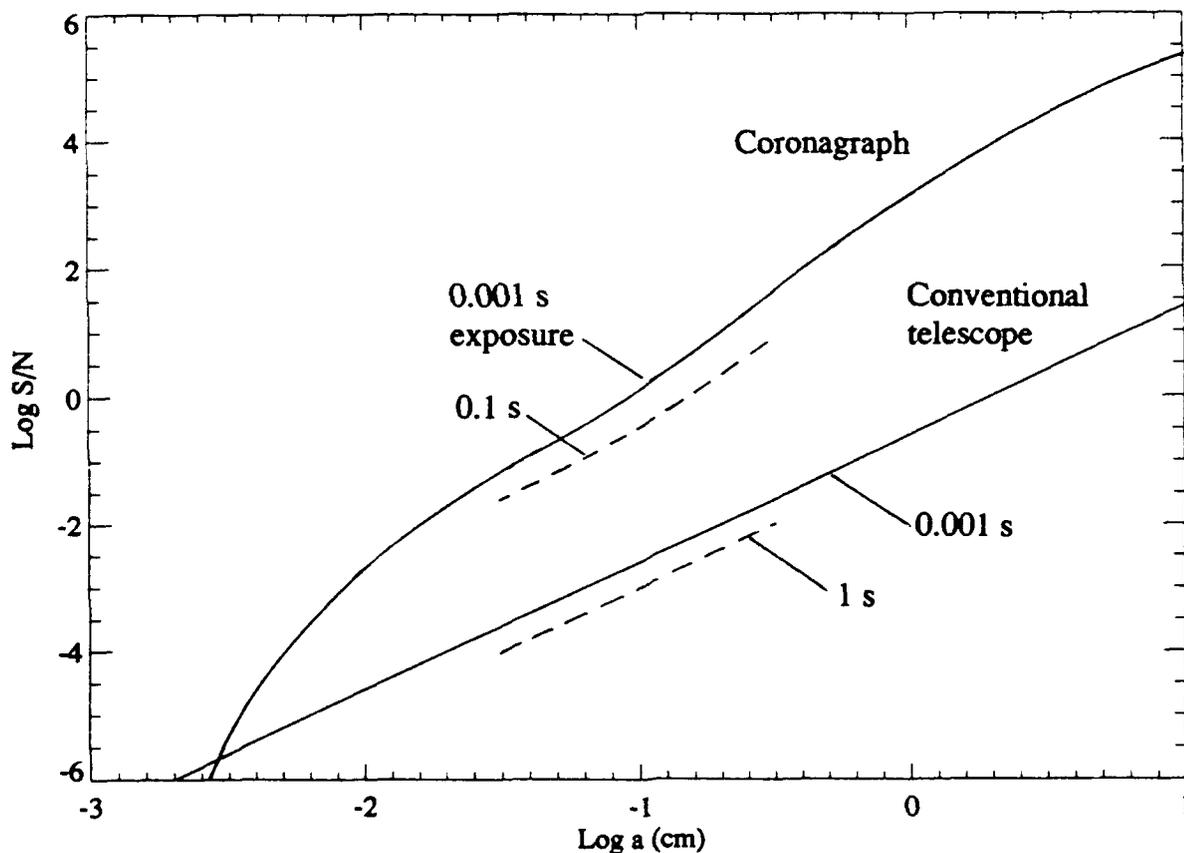


Figure 1. Per-pixel signal/noise ratio as a function of debris diameter. Compared are a 2-m ground-based coronagraph observing debris in 500-km orbit at an angular distance 0.3 solar radii outside the solar limb, and a 2-m ground-based conventional telescope observing the same debris at night.

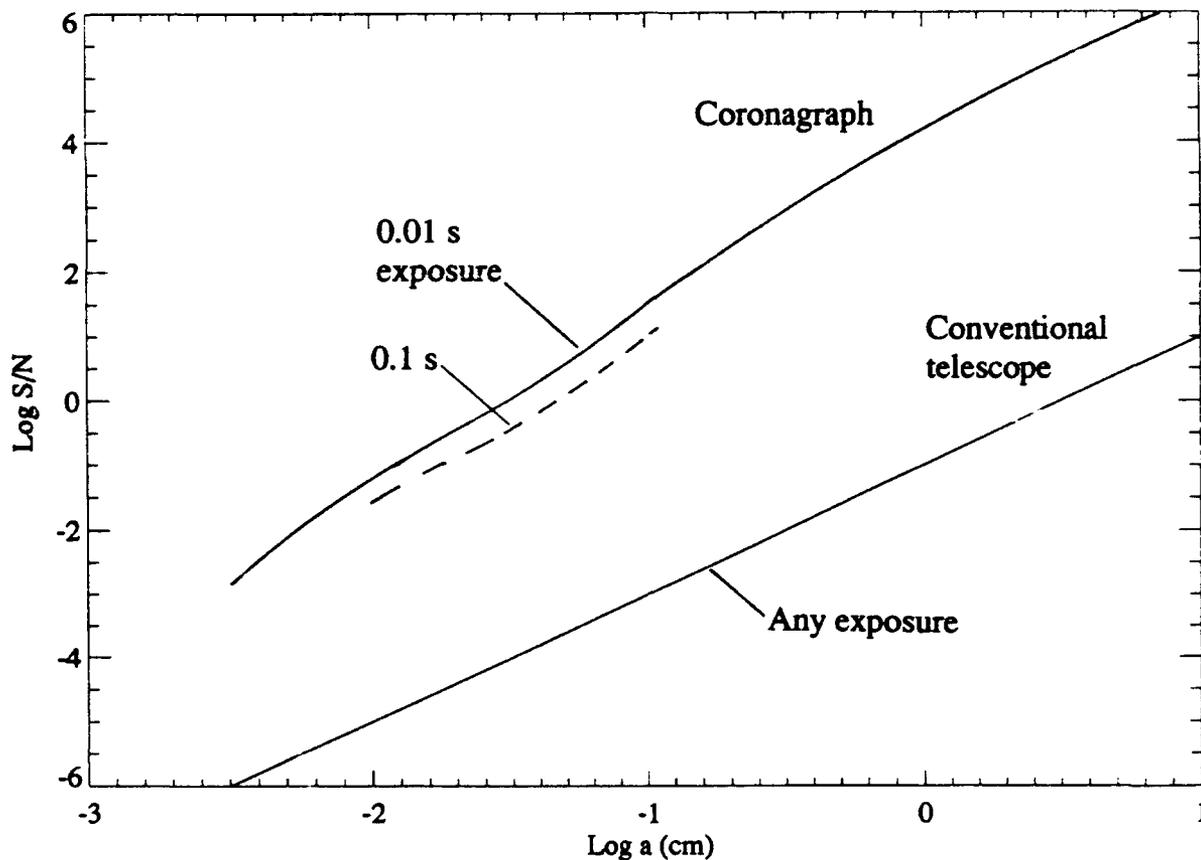


Figure 2. Per-pixel signal/noise ratio as a function of debris diameter. Compared are a 20-cm space-based coronagraph observing debris 0.3 solar radii outside the solar limb at distance 100 km and moving 1 km/s across the line of sight, and a 20-cm space-based conventional telescope observing the same debris via backscattered radiation.

Several important considerations relating to either ground-based or space-based coronagraphic observations of debris are noted here. First, coronagraphs must necessarily operate in a stare-mode, as the instrument must remain pointed at the sun at all times. Some quasi tracking can be achieved, in principle, by effectively moving the focal plane detector. However, because the bright background observed by the coronagraph readily saturates the detector, this focal-plane tracking can be used only to a limited extent, unless there is a vast improvement in detector read-out rates. In any case, orbital elements will not be obtained, and the data would be useful primarily in statistical studies of the debris population. Second, the S/N calculations presented here are based on diffraction from ideal particles (circular disks). Actual debris is more likely to have irregular shapes and rough edges, requiring revised models for the diffraction patterns used in calculating the debris signal. However, periodic glint reflection from plane surfaces on some irregularly-shaped, slowly rotating debris (a likely scenario), could enhance detection probability compared with that of a smooth sphere. Third, subtraction of the sky

background may prove difficult, as the terrestrial atmosphere contains small, moving particulates producing a transient and spatially variable background signal. Reasonable discrimination between such traces and those of debris might be possible on the basis of typical velocities of orbital debris and the typical direction and fast transit times of nearby particles under strong wind conditions, or random and nonlinear traces under quiescent conditions.

In summary, we suggest that the use of coronagraphs, either on the ground or in space, appears to offer an excellent prospect for space debris detection. Any factor, F , by which the limiting size of observable debris can be reduced will, as a consequence of the power-law distribution of the debris population, result in an increase in debris detection rate by a factor $\approx F^{1.6}$. The coronagraph's measurements are independent of albedo, and the advantages that stem from its unique characteristics are manifested in a debris size range not easily observed by other means.

Schuerman, D.W., Beeson, D.E., and Giovane, F.: 1977, *App. Opt.* **16**, 1591.