SPACE BORNE PHOTOMETRY PERTURBATIONS FROM SOLAR LIGHT SCATTERED BY DEBRIS

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ABSTRACT

We study the possible impairment of the solar light scattered by small debris, measured by high photometric quality instrument, during space borne observations. We compute the contribution of the fragments released on orbit by the host satellite and of the debris already present in the background. Preliminary results show that these spurious fluxes can reach the level of the collected Zodiacal Light: there are the main components of the noise level which affect the scientific signal. On the future, threats on high sensitivity photometric missions should rise with the increasing launches of satellite constellations if no legislation controls the design of satellites.

1. INTRODUCTION

Artificial satellites are concerned by collisional erosion and disruption due to interplanetary grains, mainly during meteor storms [1]. Such processes generate solid particles called debris. Other sources of debris come from degradations of spacecrafts (and upper stages of launchers), induced by solar irradiation, cosmic rays and previous generations of man-made orbital dust. Thermal phenomena such as those experienced during terminator crossings are also sources of solid particles. Likewise, mechanical operations and spacecraft manoeuvring by means of thrust exhaust, contaminate space. In addition solid particles carried up from ground during launch operations and those exhausted from solid-fuel rockets create a number of particulates (see for example [2]).

Some space missions have been partly devoted to the study of debris released on orbit (see for example [2], [3]). Other missions detect solid particles produced during previous collisional events. From these measurements, the size distribution of the debris, which depends on space locations and time, can be deduced. This allows to evaluate potential damages on a satellite and its instruments during a mission. But instruments performances can also be reduced because of sunlight and earthshine scattered by solid particles in the field of view. Recently, McNally and Rast [4] have shown that the sunlight reflected by satellites and largest debris threats the photometric quality of space-based optical astronomical observations. Presently we study the level of the solar flux scattered by a population of small debris (whose size is lower than 10 cm) in a field of view of a high sensitivity instrument. Following a broad review, in the next Section, of the main properties of space debris, we introduce in Section 3 a high photometric quality mission, COROT. Section 4 is devoted to a first estimate of the solar flux scattered by debris located in the field of view of this instrument. We distinguish between the contribution of the fragments released on orbit by the satellite itself and the contribution of the debris in the background, and we compare them with the predicted measured Zodiacal Light. Our conclusions are presented in Section 5.

2. SPACE DEBRIS

2.1 Sources of space debris.

Since the beginning of human activity in space in 1957, objects associated with more than 4000 launches have placed hardware in low Earth (LEO) and geosynchronous orbits (GEO), with some high eccentricity objects connecting these orbits to low altitude. These objects are classified as debris if they remain in orbit but no longer serve any useful purpose. They include large payloads as well as small elements released during launch operations. Many of these objects have been fragmented by explosions and collisions. These events can inject debris into altitudes far removed from the place they occur and therefore expose many other programs to a risk of damaging collision. The largest, with a diameter above a few cm are tracked by the U.S. Space Surveillance Network (SSN) and catalogued (about 8600) [5]. The sizes and mass of fragmentation debris can vary from a few square meters in average cross-sectional area and hundreds of kilograms to less than a few square millimetre and milligram, as shown by laboratory experiments [6]. Although the interaction of the sunlight with these large debris is not taken into account in this study, they must be mentioned as a significant source of small debris.

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Far more numerous are the smallest debris with a diameter between 1 cm and 1 µm; amongst them : the aluminium oxyde particles associated with the solid rocket motor firings, the NaK droplets released from the RORSAT satellites, the ejecta produced upon hypervelocity impacts on the spacecraft surfaces and the by-products of surface degradation of material under the space environment (ultra violet radiation, atomic oxygen erosion and thermal cycling).

Moreover, in 1961 and 1963, two MIDAS satellites ejected millions of copper needles (whose size is 18 mm long by 25 microns in diameter [7] at an altitude of 3200 km (West Ford needles project) to act as a passive reflectors for relaying military communications. The orbital inclination (96°) was chosen so that the combined effects of earth gravitational effect and influence of solar radiation pressure would be in resonance and cause the needles to renter the earth atmosphere in a few years. However this mechanism was in part inefficient and most of particles are still in orbit.

2.2 Models for space debris distribution.

Several models are currently describing the orbital debris environment. The Meteoroid And Space debris Terrestrial Environment Reference (MASTER) model has been developed under ESA contract [8]. Current version is limited to particles of diameter larger than 100 microns. Two other models, the Integrated Debris Evolution Suite (IDES) model [9] and the Space Debris Model (SDM) [10] have been proposed but there are limited to particles larger than 1 mm. The NASA ORbital Debris Model (ORDEM96) is restricted to circular target orbits for altitudes lower than 2000 km [11]. It is mainly based on results from observation of space debris (Haystack radar and LDEF). It offers directional flux information and is valid for particle diameters down to 1 micron. It discriminates by particles on source terms as intact satellites, large fragments, small fragments, paint flakes, aluminium oxide particles and NaK particles.

Seeing that ORDEM96 include micron-sized particles, it is presently the best model to study the spurious solar light scattered by the population of small debris, which are supposed to be spherical. The cumulative flux given by this model, on a polar orbit, is shown on the Fig.1 for particles whose sizes (diameters) are greater than or equal to 1×10^{-4} cm . Data which concern smaller debris are deduced from in-situ measurements, on the MIR space station [12]. Since the model is restricted to altitude lower than 2000 km, clusters of long lived copper dipoles released in the framework of the West Ford Needles project are not included in the cumulative flux.

In the present study we will suppose that the size distribution of debris deduced from Fig.1 is valid from an altitude of 800 km to 1500 km. Beyond that the space density will be supposed equal to 0.

On Fig.1 we have shown for comparison the cumulative flux of interplanetary dust.

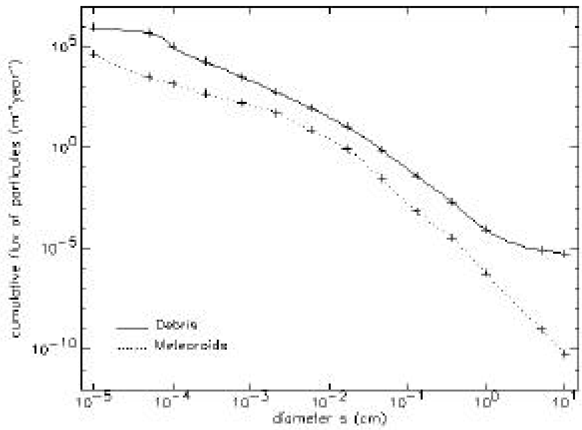

Fig.1. Cumulative flux of orbital debris and meteoroids [13] impacting a spacecraft, per square meter per year (orbit 850 km altitude, 98° inclination; perspective for year 2004).

3. THE SPACE MISSION COROT

This mission is mainly dedicated to asteroseismology and research of exoplanets. To reach these objectives, a polar orbit and an altitude of 850 km have been chosen; each field of view will be observed continuously during a period of 5 months. During each period, the asteroseismology program will study some stars (typically 5 stars) while the exoplanets program will try to detect planetary systems from transits in front of thousands of stars. For this, high precision photometric observations will be performed using an afocal telescope with an entrance pupil of 27 cm and a focal length of 1200 mm. The field of view of each program (1.5° x 3°) is covered with 2 EEV CCD (each of them have 2048x2048 pixels, the size of a pixel is 13.5 microns x 13.5 microns). The surface of the image of a point source at infinite distance is 172 (resp. 43) pixels for the asteroseismology (resp. exoplanets) channel.

The stellar flux collected by the telescope could be disturbed by two sources of spurious light: the sunlight reflected by Earth as well as scattered by dust (interplanetary grains and debris). The light coming from Earth will be attenuated by a baffle in front of the telescope: the amplitude of this periodic noise, which would affect the Fourier analysis of the seismic data, will be reduce to 1 photoelectron $px^{-1}\ s^{-1}$. Conversely the scattering of the sunlight by dust cannot be attenuated. It induces a "constant" component (w.r.t. the exposure time) as well as discret periodic or not periodic events: they affect the two channels if their amplitudes reach 10 photoelectrons px^{-1} s^{-1}. These values must be compared with an evaluation of the signal induced by the flux scattered by dust.

4. ESTIMATION OF THE SCATTERED FLUX COLLECTED BY COROT

4.1 Solar flux scattered by debris shed from the satellite

According to in situ measurements (see for example [2]), the speed of the debris, shed from COROT, should be very low w.r.t. the satellite: debris whose sizes are included between 1 and 100 microns have speeds included 20 and 0.2 cm s^{-1} [2]. When a debris is moving along the line of sight, the size of its image decreases until it reaches the size of the image of a point source at infinite distance.

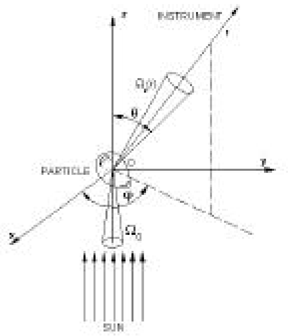

Fig.2. Geometric parameters of the sunlight-particle interaction and instrumental detection

The scattered flux collected by COROT is calculated from the differential scattering cross section of the debris

$$\left(\frac{dC_{sca}}{d\Omega}\right) \qquad \text{with} \qquad d\Omega = \sin q \; dq \; dj \;,$$

where q is the scattering angle, j the azimuth angle and C_{sca} the scattering cross section of the debris (Fig.2).

The differential scattering cross section depends on the geometrical and physical characteristics of the particle (size s, state of surface, complex indices of refraction n, ...) and on the parameters of the sunlight-particle interaction (q, j, wavelength l of the incident light, ...). Since particles are supposed to be spherical (ORDEM96 §2.2), the differential scattering cross section is obtained from the Mie theory. Moreover stratospheric captures of debris have shown that aluminium oxide particle have mainly spherical shape: we will suppose in this first estimate that debris are made of such material.

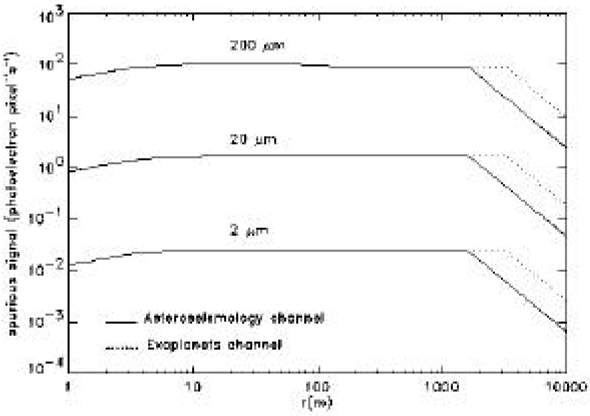

Fig.3. Signal delivered by a pixel of a spurious image (photoelectron px^{-1} s^{-1}) of debris of three different diameters, in function of their distance r from the aperture of the baffle.

Let $\Omega_p(r)$ the solid angle which subtends (from r) the area of the entrance pupil. The part of the cross section which induces spurious flux in the instrument is given by

$$C_i(s,r) = \int_{\Omega_P(r)} \left(\frac{dC_{sca}}{d\Omega}\right) d\Omega \quad (in\; cm^2) \qquad (1)$$

Let $B_O(l)$ the surface brightness of the sun ($in\, W\; cm^{-2}\; sterad^{-1}\; m^{-1}$), which depends on the wavelength l, Δl the effective spectral band pass, $T(l)$ the effective transmission of optic, $E(l)$ the effective quantum efficiency of the detectors, Ω_0 the solid angle which subtends (from the debris) the solar disk. The flux of the light scattered by the debris and collected by the entrance pupil is given by

$$B_0(l)\,\Omega_0\,\Delta l \int_{\Omega_P(r)} \left(\frac{dC_{sca}}{d\Omega}\right) d\Omega \quad (in\, W) \qquad (2)$$

Let us suppose that the intensity in an image of a debris is uniformly distributed. Then the scattered light induces in each pixel of the asteroseismology channel image a spurious signal $F_s(s,r)$ given by

$$F_s(s,r) = \frac{T(l)\,E(l)}{N_s(r)} B_0(l)\,\Omega_0\,\Delta l\,C_i(s,r)$$

$$(in\ photoelectrons\ px^{-1}s^{-1}) \qquad (3)$$

where $N_s(r)$ is the surface of the image (in pixel). A similar expression is obtained for the exoplanets channel. Both spurious signals are displayed on Fig 3. We show that fragments larger than 20 microns induce a non negligible spurious signal which can affect the scientific data. Since in situ measurements reveal that the size distribution can peak around 15 microns [2], the perturbation might be taken into account in the data processing.

4.2. Solar flux scattered by debris located in the background

An estimation of the spurious light, generated by debris located in the background, depends on their quantity in the field of view. We must first calculate the volume V_A taken up by debris whose cumulative flux $\mathsf{F}(s)$ is shown in Fig.1. We compare it with the volume V which contains the debris located in the field of view. We can deduce, for each size, the quantity of particles contained in the field in function of their position r. Then from the scattering cross section we can deduce the spurious light collected by each channel of the instrument.

Let $r_{\max}$ the deep length of the field where debris are found (if we suppose that the line of sight is perpendicular to the plane of the orbit, $r_{\max} \approx 3000\ km$), r_{bp} the distance between the aperture of the baffle and the entrance pupil $(r_{bp} << r_{\max})$, Ω_V the field of view of a channel. The volume V is given by

$$V(r_{\max}) = \frac{\left[(r_{\max} - r_{bp})^3 - r_{bp}^3\right]}{3}\,\Omega_V \qquad (4)$$

The quantity of debris in the field of view of a channel whose size (or mean diameter) is included between s and $(s+ds)$ is given by

$$dN(s, s+ds) = [\mathsf{F}(s) - \mathsf{F}(s+ds)]\frac{V(r_{\max})}{V_A}$$
$$= -\frac{d\mathsf{F}(s)}{ds}\frac{V(r_{\max})}{V_A}ds \qquad (5)$$

As the part of the cross section which induces the spurious light in the instrument depends on $\Omega_p(r)$, i.e. is a function of r, we must consider the part of dN located between r and $r+dr$ and given by

$$d^2N(r, r+dr, s, s+ds) =$$
$$= -\frac{1}{V_A}\frac{dV}{dr}\frac{d\mathsf{F}}{ds}dr\,ds \qquad (6)$$

Let us suppose that the spatial density of debris is small. Then the solar light scattered by debris located in the background should induce from each pixel of the asteroseismology detectors a mean spurious signal $F_s^b(r_{\max})$ given by

$$F_s^b(r_{\max}) = -\frac{1}{V_A}\int_0^{r_{\max}} dr\,\frac{dV(r)}{dr}\times$$
$$\int_{s_{\min}}^{s_{\max}} ds\,\frac{d\mathsf{F}(s)}{ds}F_s(s,r)$$

$$(in\ photoelectrons\ px^{-1}\ s^{-1}) \qquad (7)$$

(with $s_{\min} = 10^{-5}\ cm$ and $s_{\max} = 10\ cm$, see Fig.1). The spurious signal measured by the exoplanets channel is given by a similar expression: a complete study is proposed elsewhere by Mandeville, Perrin and Vuillemin [15]. The great number of debris randomly distributed in the field of view would suggest that the signal F_s^b is the same from each pixel. As a matter of fact the problem is much more complex. At a given altitude, debris can be divided into two components:

- particles on elliptic trajectories: their speeds with respect to the satellite are very high; the flux they scatter tends to the uniform component,
- particles on circular orbits: some of them can have very low speed with respect to the satellite. During an exposure, their images only move slightly. The superposition of such images can induce local increases of irradiance ("light-peaks") which disappear and reappear in other parts of the detectors generating a "light-lapping".

The proportion p of debris on circular trajectories with respect to debris on elliptic orbits is not well known. If

$h = 900\ km$, $0.5 \le p \le 0.85$, ORDEM96 uses $p = 80\%$: we choose this value. We suppose that a "light-peak" takes place during an exposure if the relative shift of superimposed images of particles are lower than the radius of the smallest image. Let a_c the mean angular radius of a channel ($a_c = 1.05°$). A "light-peak" can be observed in the asteroseismology channel if the shifts $D_s(r)$ are lower than or equal to

$$D_s(r) = \left[\frac{N_s(\infty)}{N_t}\right]^{\frac{1}{2}} \left(r + r_{bp}\right) tg a_c . \qquad (8)$$

where N_t is the number of pixels for each channel.

Let n_0 the speed of the satellite (and solid particles) on circular orbit at altitude h. During an exposure time Δt_s, the highest value of the angle a_s between the direction of the speeds of the satellite and particles such that the shifts of the superimposed images are lower than or equal to $D_s(r)$ is given by

$$a_s(r) = \cos^{-1}\left[\frac{v_0\ \Delta t_s - D_s(r)}{v_0\ \Delta t_s}\right] \qquad (9)$$

Consequently the proportion of superimposed images is $a_s(r)/p$. In summary the proportion $(1-p)$ of debris on elliptic orbit and the proportion $p(1 - a_s/p)$ of debris on circular orbits induce the uniform spurious component. The proportion pa_s/p of debris on circular orbits contributes to the "light-peaks". To estimate the intensity of the "light-peaks", we consider the particles whose sizes are included between s and $(s + ds)$, which are found in the volume $V(r)$ of the field. When r reaches the value $r_1(s)$, the images of the particles contained in $V(r_1(s))$ cover once the detectors. Among these $\mathrm{N}(r_1(s))$ images, a proportion $pa_s/p = P(r_1(s))$ are quasi steady (during the exposure time Δt_s). In a same manner, when r reaches the value $r_2(s)$ the images of the particles in the volume $[V(r_2(s)) - V(r_1(s))]$ cover once more the detectors. Among these $\mathrm{N}(r_2(s))$ images, a proportion $P(r_2(s))$ are quasi steady. When a distance $r_1(s)$ is reached, the pixels contained in the

$$\mathrm{N}(r_1(s))\, P(r_1(s)) + \mathrm{N}(r_2(s))\, P(r_2(s)) + ... \\ + \mathrm{N}(r_i(s))\, P(r_i(s))$$

images is greater than N_t: two steady images at least are superimposed. This operating process is carried on until $r = r_{\max}$ and extend to the size distribution of debris. The "light-peaks" intensity also depends on the size of the debris: the largest fragment, the highest intensity. But the superposition of steady images of small debris occurs more frequently than the superposition of largest ones (§2.2). Then the intensity of the "light-peaks" must be expressed as a distribution or probability law. Let x the value of the signal delivered by a pixel of a "light-peak" and $r(u)du$ the probability that x is included between u and $(u + du)$. The function

$$G(u) = 1 - \int_0^u r(w)\, dw \qquad (10)$$

expresses the cumulative probability that this value is greater than or equal to u . This function is showed on Fig.4.

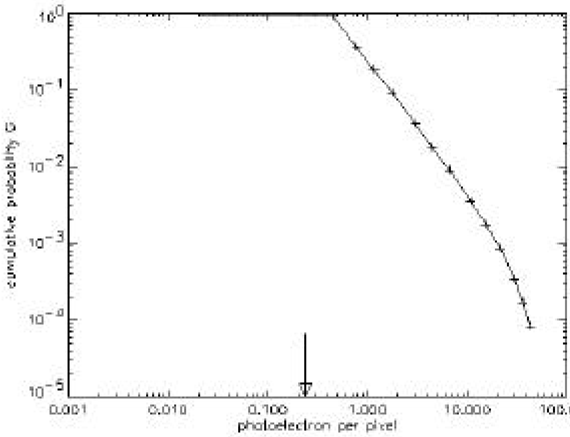

Fig.4. Cumulative probability of "light-peaks" in the asteroseismology channel with respect to their intensity. The arrow gives the mean value of the uniform spurious component obtained during an exposure time of $\Delta t_s = 1\ s$.

As the "light-peaks" collected by the asteroseismology channel cover 7% they can disturb the scientific data .

We compare these results with the signal induced by the Zodiacal Light [16], the solar light scattered by interplanetary grains, collected by COROT. Fig. 5 shows the values of the signal for different fields of view (characterised by their ecliptic latitude) w.r.t. the ecliptic longitude during an half of a period of observation: the “light peaks” as well as the light scattered by fragments released in orbit can reached the level of the Zodiacal Light.

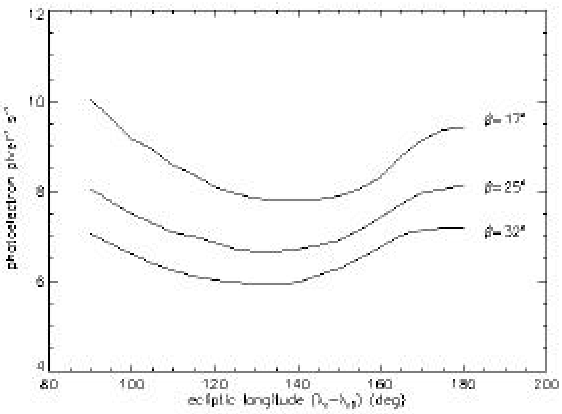

Fig.5. Spurious signal (in photoelectron px^{-1} s^{-1}) versus the ecliptic longitude induced by the Zodiacal Light for the three selected fields of view characterised by their ecliptic longitude b .

5. CONCLUSION

We have shown that the sunlight scattered by small debris can seriously affect the photometry of high sensitivity instruments. The uniform component of this spurious light, induced by those of the debris in the background, is not presently a true problem because it is more than one order of magnitude lower than the Zodiacal Light. On the contrary, the peaks of light generated by this debris as well as the light scattered by fragments released in orbit can reach the level of the Zodiacal Light. On the future threats on high sensitivity missions should raise with the increasing number of satellites if no appropriate mitigation measures are devised. These threats incite us to improve our rather rough model. Accuracy of computation can be increased by taking into account the various compositions of the debris, their various shapes (for example needles) and states of the surface. These improvements are in progress. Moreover a better knowledge of the size distribution of the small debris and its temporal evolution will be also welcomed. These informations might be obtained with dedicated dust detectors as passenger instruments on as much as possible space missions.

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