CALCULATING THE X-RAY FLUORESCENCE FROM THE PLANET MERCURY DUE TO HIGH-ENERGY ELECTRONS.

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Introduction: The least-studied terrestrial planet is Mercury due to its proximity to the Sun, which makes telescopic observations and spacecraft encounters difficult. Our lack of knowledge about Mercury should change in the near future due to the recent launching of MESSENGER, a Mercury orbiter. Another mission (BepiColombo) is currently being planned. The x-ray spectrometer on MESSENGER (and planned for BepiColombo) can characterize the elemental composition of a planetary surface by measuring emitted fluorescent x-rays. If electrons are ejected from an atom's inner shell by interaction with energetic particles such as photons, electrons, or ions, electrons from an outer shell can transfer to the inner shell. Characteristic x-rays are then emitted with energies that are the difference between the binding energy of the ion in its excited state and that of the ion in its ground state. Because each element has a unique set of energy levels, each element emits x-rays at a unique set of energies.

Electrons and ions usually do not have the needed flux at high energies to cause significant x-ray fluorescence on most planetary bodies. This is not the case for Mercury where high-energy particles were detected during the Mariner 10 flybys [1]. Mercury has an intrinsic magnetic field that deflects the solar wind, resulting in a bow shock in the solar wind and a magnetospheric cavity. Electrons and ions accelerated in the magnetosphere tend to follow its magnetic field lines and can impact the surface on Mercury's dark side

Modeling has been done to determine if x-ray fluorescence resulting from the impact of high-energy electrons accelerated in Mercury's magnetosphere can be detected by MESSENGER. Our goal is to understand how much bulk chemical information can be obtained from x-ray fluorescence measurements on the dark side of Mercury.

Modeling: Our modeling utilizes the Monte Carlo transport method to simulate, on a particle-by-particle basis, the trajectories of incident particles as they strike Mercury and the secondary particles that they produce. The code chosen for this study is PENELOPE (PENetration and Energy Loss Of Positrons and Electrons in matter) (2001 version) [2]. The incident particle spectrum is inputted as a probability distribution function over a series of energies. Photons emitted or scattered in all directions are tracked. Calculated ratios of pro-

duced fluorescent photons for a variety of elements relative to silicon tend to match ratios derived by analytical models within ±5%.

The surface is assumed to be infinite in length and width. To simulate a regolith, the surface is covered with cubes (20 μm in diameter and 20 μm apart). Each run is 3 hours and two sets of runs with different random numbers are averaged. The incident particle flux is assumed to be perpendicular to the surface.

Electron fluxes at Mercury with energies high enough to excite most elements were not very well-defined by the Mariner 10 measurements since electron spectra were only directly measured from ~0.01 to ~0.70 keV and >175 keV. Indirect measurements by Mariner 10 instruments determined that a significant ~35-175 keV electron flux was present during sub-storm-like intervals, but could not accurately determine the spectral shape or the flux level [3, 4].

To do the modeling, the fluxes of characteristic photons emitted by Mg, Al, and Si for a particular surface composition that will produce detectable fluorescence on the sunlit side were first calculated and then the electron flux needed to reproduce this fluorescence flux on the dark side was determined. Only these three elements were used since fluorescence can be detected for these elements during both solar flare and "quiet" sun conditions. Starr et al. [5] estimated integration times for MESSENGER to identify different elements on Mercury's surface for a theoretical surface composition [6]. The integration time is the interval of time used to collect photons of light on a detector and build-up a strong signal. The integration times [5] are scaled from results for NEAR-Shoemaker observations of 433 Eros [7] during a May 4th 2000 solar flare and the "quiet" sun during July 2000. The integration times at the 10% uncertainty level during the solar flare were 2-3 minutes for Mg and Si and 22-50 minutes for Al. For the "quiet" sun, the integration times were 5-11 minutes for Mg, 7-18 minutes for Si, and 2-8 hours for Al.

To determine the emitted fluorescent flux that will produce detectable fluorescence on the sunlit side, the incident photon fluxes during a solar flare and the "quiet" sun used by Starr et al. [5] in their analysis of integration times for different elements by MESSENGER had to be estimated. The average temperature of the May 4th 2000 solar flare was estimated

to be 14.5 million Kelvin [7] while the "quiet" sun during July 2000 was estimated to have a temperature of 4 million Kelvin. Theoretical x-ray fluxes were generated for solar temperatures of both 4 and 14.5 million Kelvin in units of particles/cm^2-s-keV. A program (CHIANTI) [8, 9] was used to estimate emission lines for those temperatures, assuming a coronal abundance of elements. These fluxes were then scaled to Mercury's orbit. Mercury's surface composition was assumed to be the same as the one used by Starr et al. [5].

The program computes the probability that fluorescent photons are emitted for each inputted energy range relative to the number of incident particles that strike the surface. The probability that photons were emitted by each particular element was determined by taking the probability that photons were emitted at the elements Kα energies. These probabilities were multiplied by the number of photons striking the surface for that energy range to determine the number of fluorescent photons emitted by a particular element by incident photons. For the solar flare, the total flux over the energy range is 1.91×10^8 photons/cm^2-s and for the "quiet" sun, the total flux over the energy range is 2.51×10^7 photons/cm^2-s.

The probabilities that fluorescent photons would be emitted for simplified energetic electron flux distributions were then calculated. The spectral shape of the differential number flux of electrons was assumed to be constant from 1 keV out to a maximum energy (10 and 35 keV, respectively) and then drop off to zero, similar to plasma sheet particle energy spectra observed in Earth's disturbed magnetosphere [10] and implied by the measurements at Mercury. All analytical conditions were the same except for the use of electrons instead of photons as the exciting source.

To determine the electron flux needed to produce integration times similar to those for the solar flare and the "quiet" sun conditions, the number of fluorescent photons emitted by Mg, Al, and Si during the solar flare and the "quiet" sun were divided by the probabilities that a fluorescent photon from those same elements was emitted due to incident electrons. The resulting number is the total flux of incident electrons/cm^2-s needed to produce equivalent fluorescence for that element. For each inputted electron flux distribution, the results for Mg, Al, and Si were averaged to produce average electron fluxes that replicated the estimated integration times for the solar flare and the "quiet" sun conditions. To determine fluxes in units of electrons/cm^2-s-keV, the total flux was divided by the energy range in keV.

Results: To produce integration times similar to a solar flare for the flat distribution from 1 to 10 keV, the needed average electron flux is $\sim2.3 \times 10^8$ electrons/cm^2-s-keV while for a flat distribution from 1 to 35 keV, the needed average flux is $\sim1.4 \times 10^7$ electrons/cm^2-s-keV. For integration times similar to the "quiet" sun for the flat distribution from 1 to 10 keV, the needed average flux is $\sim3.8 \times 10^7$ electrons/cm^2-s-keV while for a flat distribution from 1 to 35 keV, the needed average flux is $\sim2.5 \times 10^6$ electrons/cm^2-s-keV.

Do electron fluxes of this magnitude appear possible? One published Mercury substorm plasma electron energy spectrum [11] had a flux with a nearly constant intensity from ~0.01 to ~0.70 keV of $\sim5 \times 10^7$ electrons/cm^2-s-sr-keV, which is equivalent to $\sim3 \times 10^8$ electrons/cm^2-s-keV. If this substorm electron flux stayed constant out to 10 keV, fluorescence due to Mg, Al, and Si should be easily detected by MESSENGER with integration times similar to observations of a solar flare on Mercury's sunlit side. If this substorm electron flux stayed constant out to at least 35 keV, much shorter integration times would be expected.

Conclusions: It appears possible that x-ray fluorescence will be detected on the dark side of Mercury due to impacting high-energy electrons. Further work must be done to determine how well the composition of Mercury can actually be determined from x-ray measurements on the dark side. Both MESSENGER and BepiColumbo will directly measure the high-energy electron flux around Mercury.

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