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STUDY OF MASS FLOW DISTRIBUTION AND CHEMICAL COMPOSITION OF COMETS FROM SOLAR INDUCED X-RAY FLUORESCENCE

FINAL REPORT

Grant NSG-7380

October 1, 1977 to September 30, 1978

Principal Investigator
Dr. Paul Gorenstein

August 1979

Prepared for
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory and the Harvard College Observatory are members of the Center for Astrophysics

The NASA Technical Officer for this grant is Bertram Donn, SL/Planetary Programs, NASA, Washington, D.C. 20546.
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1.0 INTRODUCTION

The objective of this study was to evaluate the expected performance of an X-ray detector as an instrument aboard a mission to a comet. The functions of the detector are both non-dispersive analysis of chemical composition and measurement of mass flow from the comet nucleus. Measurements are to be carried out at a distance from the comet. The approach distances considered are of the order of 1000 km and 100 km. For completeness, the approach as described in the original proposal is included here as Appendix A. In particular, we considered a new type of X-ray detector, a proportional scintillation detector, as an X-ray counter for non-dispersive elemental analysis.

As part of the work effort, we tried to be responsive to questions from the JPL comet mission study team concerning the specifications of an X-ray instrument. As a result, our engineering group made a preliminary design calculating weights, volume, power, and telemetry requirements. These results are included as Appendix B.

2.0 THE PROPORTIONAL SCINTILLATION COUNTER

We considered the proportional scintillation counter as a possible alternative to the conventional proportional counter for non-dispersive elemental analysis of X-ray fluorescence lines induced by solar X-ray radiation. The principal advantage of this detector is its superior energy resolution. A solid state detector which has even better energy resolution is out of the question for a comet mission because of its small area and its requirement for low temperature. Both the engineering requirements and the scientific performance of the proportional scintillation detector were considered.
2.1 ENGINEERING REQUIREMENTS OF THE PROPORTIONAL SCINTILLATION COUNTER

The most significant factor in the proportional scintillation counter as compared to the conventional proportional counter is the necessity for keeping the xenon gas pure for a long period. While we were studying this problem in the laboratory, a paper was issued by the High Energy Astrophysics Division of the Space Science Department of the European Space Agency (Peacock, et al., to be published in Nuclear Instruments and Methods). They seem to have succeeded in making a sealed counter with good energy resolution, that was not contaminated by outgassing from internal materials. I describe the technique of the ESA group as related in their paper which was the result of a much more substantial effort than ours.

The ESA counter body was constructed from 5mm thick machinable ceramic sections. The X-ray entrance window, a spherical section beryllium dome 450 µm thick, interfaced with the ceramic cone via a stainless steel flange. The exit window was made of 4 mm thick UV transmissive quartz. The two spherical section grids created the focussing electric field and a plane grid was placed close to the exit window to prevent electrostatic charging. These grids were constructed from sheets of molybdenum, which were formed to shape and electro-etched. Six gold-plated molybdenum focussing rings, each 3 mm wide, were deposited on the inside of the cone walls of the drift region to control fixed potentials along the cone and thereby to minimize the effect of external influences on the drift region field and electrostatic charging of the ceramic. No resistive coating of the ceramic cone walls was included.
The counters were assembled using ultra-high vacuum techniques and baked out at 300°C to minimize the possibility of contamination of the 760 Torr purified research grade Xenon filling over long periods. Two SAES AP5 getters were mounted close to the exit window to enable the maintenance of high gas purity.

No wavelength shifting material was used in these counters, the UV scintillations (1500 - 1950 Å) being detected by an EMI D319 photomultiplier. Since wavelength shifters such as p-terphenyl have quantum efficiencies of < 40% and can introduce hydrocarbon impurities into the counter, they offer no real advantage. Furthermore, such materials may degrade over long periods, particularly in a space environment.

Our conclusion is that this technique could probably be used to make a detector that would be suitable for a long duration comet mission.

2.2 EXPECTED SCIENTIFIC PERFORMANCE OF THE PROPORTIONAL SCINTILLATION DETECTOR (PS)

The desired measurement is passive analysis of the chemical composition of a comet. The measurements are to be carried out at distances of 100-1000 km from the nucleus and must be accomplished in a matter of hours. We consider only non-dispersive techniques such as was used successfully to map the chemical composition of the region of the Moon covered by Apollo 15 and Apollo 16. Dispersive techniques do not seem to be practical at these distances because of their low overall throughput.

Computer simulations were carried out of the solar induced X-ray fluorescence from a comet. We assumed a basalt type composition to facilitate the use of some existing software and constant tables. We assumed a solar X-ray spectrum with a temperature of $2 \times 10^6$ K. The PS offers an energy resolution of 10% at 5.9 keV as
compared to the 25% resolution of a conventional proportional counter. The objective of these studies is to determine what benefit, if any, would be derived from the improved energy resolution. If the energy resolution were sufficiently improved over a conventional proportional counter, then one could dispense with one or more filtered detectors in a non-dispersive multi-detector analysis system.

The simulation included fluorescence X-rays from the material, scattered solar X-rays, and the energy resolution of the detector was folded into the calculation. Although the cometary material will certainly be different than basalt, in particular it will contain water, the conclusions are expected to be similar at least qualitatively.

Figure 1 is a comparison of the X-ray spectra of a basalt "comet" illuminated by the Sun as seen by three detectors having energy resolutions, ΔE/E, of 1%, 10%, and 25% at 5.9 keV. (ΔE/E is assumed to decrease with the square root of the energy.) No filters are present in front of the detectors. The 25% figure represents the energy resolution of a conventional proportional counter, and the 10% that of the proportional scintillation counter. The 1% figure is an ideal value that is not achievable in any existing non-dispersive detector, but is useful as a baseline for comparison. (The energy resolution of a typical solid state detector is about 5% at 5.9 keV.) The individual line contributions of Na, Mg, Al, and Si are not resolved in either the 25% energy resolution or the 10% resolution detector. A simple extrapolation indicates that they would also not be resolvable in a detector with 5% energy resolution-like a solid state detector. Individual lines are clearly resolvable with an energy resolution of 1%.
Figure 1. Simulated response of detectors with three values of energy resolution to the X-ray spectrum of a comet of basaltic composition that is illuminated by the Sun. The three values of resolution are: 25%, 10%, and 1% at 5.9 keV. The first is typical of a conventional proportional counter, the second that of a proportional scintillation detector, and the third that which is well beyond the capability of present non-dispersive detectors.
Figure 2 is the simulated response of PS counters with no filter, an aluminum filter, and a magnesium filter to a basalt "comet" irradiated by the Sun. While the presence of the filters effects the total number of counts substantially, it does not change the appearance of the energy spectrum significantly. That is, the energy resolution of the PS does not add much to what the filters provide.

The conclusion is that the simulated PS spectrum is not qualitatively different than that of the conventional proportional counter. It is not possible to resolve fluorescence lines of Na, Mg, Al, and Si in either case. Therefore, the PS does not avoid the necessity of using filters to separate elements. Furthermore, the solid state detector (SSD), which has only a factor of two better resolution than the PS counter will also not be able to resolve the elements. Higher Z elements such as Ca and Fe might be resolvable with a SSD, but the normal solar X-ray spectrum is too soft to produce significant fluorescent intensities of elements with $Z > 14$. In principle, a detector with a resolution of 1% could resolve the elements as shown in the figure, but no existing non-dispersive detector can achieve that resolution. A resolution of 1% is achievable with dispersive techniques but only with much greater complexity and very low throughput. With filters required in all cases, we conclude the conventional proportional counter is the preferred detector for non-dispersive analysis because of its simplicity and longer record of successful flight history.
Figure 2. Simulated response of proportional scintillation counter; unfiltered, Mg filter, and Al filter.
2.3 **POSITION SENSITIVE PROPORTIONAL COUNTER**

Having concluded that there is no alternative to the use of filters as the primary technique for non-dispersive X-ray fluorescence analysis, we consider the advantages of a position sensitive proportional counter (PSPC). The advantage of a PSPC is that a rather sophisticated set of filters could be used with a single detector, and the position sensitivity of the detector would permit separation of the different filters. Figure 3 is an illustration of the arrangement. Filter segments could include Mg, Al, and Teflon (F). Figure 4 illustrates the position sensitivity of a detector we have developed for the HEAO-2 satellite. A pattern of 0.5 mm slits separated by 3 mm, 2 mm, and 1 mm are resolved. This type of detector has been operating very successfully on HEAO-2, and a simplified version would seem to be appropriate to a comet experiment carrying out X-ray fluorescence measurements.
Figure 3. Schematic of position sensitive proportional counter with segmented filter. There are four parts, teflon, magnesium, aluminum, and open.

The Mg and Al filter used to resolve the Mg, Al, and Si group of elements.

The fluorine in the teflon helps to isolate the O fluorescence line.
Figure 4. Ability of position sensitive proportional counter (PSPC) to provide spatial resolution is illustrated. Slits of width 0.5mm are separated by 3mm, 2mm, and 1mm are resolved in output of PSPC as displayed on oscilloscope.
APPENDIX A

1.0 INTRODUCTION

A close flyby or rendezvous mission with a comet will provide an opportunity to carry out X-ray measurements that will result in new and unique information. Under the influence of solar X-ray bombardment, the fluorescence of cometary material will result in an X-ray halo that is appreciable out to distances of about ten times the radius of the nucleus. The X-rays contain information on two questions of interest: (1) the mass of the material flowing outward from the nucleus as it is heated by the Sun, and (2) the bulk abundance of the major elements in the material. The surface brightness distribution of the halo is related in a straightforward way to its density distribution function. This proposal describes an investigation of the halo with a simple X-ray detector that would be developed especially for this purpose. The objective would be to map the X-ray surface brightness distribution in a time that is of the order of a few hours. The detector would provide some energy resolution so it would be possible to estimate the abundance of major elements in the bulk material. Since the time for carrying out the measurements is short compared to the rendezvous time, it will be possible to repeat the measurements and look for changes in the amount of mass flowing from the comet as it is heated by the Sun.

As samples of what can be accomplished, we consider two types of flyby missions: (1) an encounter with a closing distance of 1,000 km and (2) a closing distance of 100 km. The instrument will be different in each case. The first type of mission will utilize a focusing X-ray telescope and a position sensitive detector and will image the cometary X-rays over a region of 3° which is about ten times the diameter of the nucleus. The detector will have good energy resolution to aid in identifying characteristic X-rays from the major elements. It will remain pointed at the comet. The closer encounter mission will utilize a non-imaging detector, also with good energy resolution. The region to be observed is now 30° so that the observations are carried out by scanning the instrument...
across the comet. The final configuration of the instrument will be determined when the final mission parameters are selected.

The approach to X-ray fluorescence measurements in a cometary mission differs substantially from that of the lunar X-ray fluorescence measurements successfully carried out from lunar orbit during the Apollo 15 and Apollo 16 missions. The primary objective here is a measurement of the mass flowing from the nucleus of the comet whereas the relative chemical composition among the magnesium, aluminum, silicon group of elements was the primary objective of the Apollo measurements. At distances greater than 100 km, we are dealing with much lower values of X-ray flux than was available from lunar orbit because the size of the comet is so much smaller. Also the instrument must necessarily be much smaller. Consequently, in order to obtain an X-ray signal that is sufficient for our purposes, it is necessary to detect soft X-rays including the 0.53 keV and 0.28 keV characteristic X-rays of oxygen and carbon. Therefore, technical problems are considerably different than in Apollo.
2.0 OBJECTIVES AND SIGNIFICANCE

The objective of this proposal program is to develop the technology necessary for the realization of the measurements described herein during a cometary flyby mission. An instrument (or critical parts thereof) will be built and studied in the laboratory. There already exists a significant technical base relating to the instruments discussed in this proposal. Our objective in this program is to apply that technology to the objectives of a potential cometary mission.

2.1 Calculation of Areal Density

The X-ray flux from a given direction looking through the halo of the comet is related to the incident solar flux and the integrated areal density of matter. As we look in directions proceeding towards the nucleus, the X-ray flux will increase up to the point until the areal density has become equal to one mean free path of absorption of the solar flux and the outgoing fluorescence radiation.

We use a simple model to derive the areal density of matter in the halo around the nucleus. We assume

(1) the radius of the nucleus, Ro, is equal to 2.5 km.
(2) the rate of mass flow from the surface of the nucleus is $3 \times 10^{-6}$ g/cm$^2$-sec.
(3) the flow velocity of the mass is 0.5 km/sec.

From the conservation of mass the density at a distance R from the center of the nucleus will fall off as the square of the distance, i.e.,

$$\rho (R) = \rho_0 \left(\frac{R_0}{R}\right)^2$$

while $\rho_0$ is the density at the distance $R_0$, the radius of the comet. Consider a direction whose closest distance to the center of the comet is $R_x$. 
Areal Density = \( A(Rx) = \int_{-\infty}^{+\infty} \rho(x) \, dx \)

\[ \rho(x) = \rho(R) = \rho_0 \left( \frac{Ro}{R} \right)^2 = \rho_0 \frac{Ro^2}{Rx + x^2} \]

\[ A(Rx) = \int_{-\infty}^{\infty} \rho_0 \frac{Ro^2}{Rx + x^2} \, dx = 2 \int_{0}^{\infty} \rho_0 \left( \frac{Ro}{Rx} \right)^2 \frac{dx}{1 + x^2/Rx^2} \]

\[ y = x/Rx \quad d = dx/Rx \]

\[ A(Rx) = 2 \rho_0 \int_{0}^{\infty} \frac{Ro^2}{Rx^2} \, Rx \frac{dy}{1 + y^2} = 2 \rho_0 \frac{Ro^2}{Rx} \tan^{-1} \left| \int_{0}^{\infty} \right| \]

\[ = \pi \rho_0 Ro \left( \frac{Ro}{Rx} \right) \]

The areal density falls off as the first power of the distance. The density at the surface, \( \rho_0 \), is equal to the mass flowing into a volume \( V \Delta t \) divided by the size of the volume:
\[ \rho_0 = \frac{3 \times 10^{-5} \text{ g/cm}^2 \text{-sec}}{4 \pi R_0^2 V_\Delta t} \]

\[ \approx \frac{3 \times 10^{-5} \text{ g/cm}^2 \text{-sec}}{6.5 \times 10^{-3} \text{ cm}^2 \text{-sec}} = 6 \times 10^{-10} \text{ g/cm}^3 \]

so \[ A(R_0) = \tau \rho_0 R_0 = \tau (6 \times 10^{-10}) (2.5 \times 10^5) = 47 \times 10^{-5} \text{ g/cm}^2 \]

\[ A(R_x) = 470 \mu \text{g/cm}^2 (R_0/R_x) \]

2.2 Solar X-Ray Flux and Oxygen Fluorescence

Solar X-rays are photoelectrically absorbed by matter. The principal observable effect is the fluorescence of the major elements that are present such as O, Mg, Al, Si, Fe, and C. Solar X-rays are also scattered. For the purpose of simplicity in estimating the count rate we will consider only one component of the return signal, the O\(\alpha\) fluorescence. Other components are present in abundance such as the C\(\alpha\) and Fe L lines so the estimate of the X-ray signal is definitely on the conservative side. The X-ray surface brightness will vary much less rapidly than the areal density because the matter which contributes is only a thin layer. The brightness is almost at its maximum value when the areal density is one mean free path of absorption. The absorption of the outgoing fluorescence lines is nearly the same as the incoming solar flux which produces it. Therefore, at radial distance, Rx, where the areal density has fallen to one tenth of a mean free path for absorption, the flux in the O line is only down about a factor of three from the point where the areal density was one free path. In fact, the total X-ray signal at Rx when integrated over the azimuthal angle is actually larger than at Ro due to the larger solid of material at larger radial distance.
To make a simple calculation of the O line flux we make the following assumptions:

(1) The comet is observed when it is a distance of 1 AU from the Sun so the solar X-ray flux incident upon the comet is $5 \times 10^{-3}$ ergs/cm$^2$-sec in both the 20-8 ˚A and 11-20 ˚A bands (same as at Earth).

(2) The composition of the comet by mass is: 40% O, 10% C, 50% (Na + Mg + Al + Si). We neglect the other elements.

The 20-8 A or 0.5-1.5 keV band is the one that is most effective in producing the O fluorescence line. Since the Sun's X-ray spectrum is describable as a thermal radiation from a hot plasma at a temperature of $2.5 \times 10^6$ K the radiation is much less intense above 2 keV. Actually, the solar spectrum contains strong O VIII and O VII line components which are very effective in fluorescing relatively cold oxygen in the comet. By neglecting the solar line radiation we will be underestimating the signal by a factor of two or three. The energy of the average photon in 20-8 ˚A is $\sim 0.8$ keV. We take the total number of photons in that band to be:

$$\frac{5 \times 10^{-3} \text{ ergs/cm}^2-\text{sec}}{1.6 \times 10^{-9} \text{ ergs/keV} \times 0.8 \text{ keV/photon}} = 4 \times 10^6 \text{ photons}$$

The absorption coefficients of the cometary material for the incident .8 keV solar X-rays and the outgoing .53 keV O fluorescence X-rays are given in the table below.

<table>
<thead>
<tr>
<th>E</th>
<th>C</th>
<th>O</th>
<th>Na + Mg + Al + Si + Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>.53 keV</td>
<td>12700</td>
<td>1230</td>
<td>$\sim 7000$</td>
</tr>
<tr>
<td>.8</td>
<td>4100</td>
<td>8200</td>
<td>$\sim 2500$</td>
</tr>
</tbody>
</table>

Mass Fraction

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>.1</td>
<td>.4</td>
<td></td>
<td>$\sim .5$</td>
</tr>
</tbody>
</table>

A-6
Average absorption coefficient at .8 keV ≈ 0.1 (1100) + 0.4 (8200) + 0.5 (2500) ≈ 1950 cm²/g.

Fraction of incident .8 keV X-rays absorbed by O = \frac{0.1 (8200)}{0.1 (1100) + 0.4 (8200) + 0.5 (2500)} = 0.65

Average absorption coefficient at .53 keV = 0.1 (12700) + 0.1 (1230) + 0.1 (7000) = 5262 cm²/g

The absorption coefficient is approximately the same for both the incoming solar X-rays and outgoing O fluorescence X-rays at ~ 5,000 cm²/g.

Consider the material at the surface. It was shown that A(Re) = 470 x 10⁻⁶ g/cm².

Therefore, \( \frac{n}{\rho} \cdot A(Re) = 5 x 10^3 \times 470 \times 10^{-6} = 2.35 \), i.e. a direction tangential to the surface of the nucleus is more than two mean free paths.

To calculate the rate of detected photons we list the following parameters:

- Fraction of solar X-rays absorbed by O = 0.65
- Fraction of O photons getting out from 1st mfp of absorption = 0.37
- Fluorescence Yield = 10⁻²
- Detector efficiency at .53 keV = 0.3

Number of O photons detected/cm²·sec·ster

\[ \frac{4 \times 10^6}{4} \times 0.65 \times 0.37 \times 10^{-2} \times 0.3 = 2.3 \times 10^2 \]

Relative to the brightness at Rx = Re we can calculate the flux at various values of Rx.
Table 2-2

<table>
<thead>
<tr>
<th>Rx</th>
<th>A(Rx)</th>
<th>A(Rx) * μ / p</th>
<th>Fraction Getting Out of 1st mfp</th>
<th>Relative X-ray Surface Brightness</th>
<th>Relative Integral Brightness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ro</td>
<td>170 x 10^{-6} g/cm²</td>
<td>2.35*</td>
<td>0.97</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2Ro</td>
<td>235</td>
<td>1.18*</td>
<td>0.97</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>4Ro</td>
<td>118</td>
<td>0.59</td>
<td>0.55</td>
<td>0.88</td>
<td>7.9</td>
</tr>
<tr>
<td>6Ro</td>
<td>78</td>
<td>0.39</td>
<td>0.68</td>
<td>0.72</td>
<td>7.9</td>
</tr>
<tr>
<td>8Ro</td>
<td>59</td>
<td>0.29</td>
<td>0.75</td>
<td>0.59</td>
<td>8.9</td>
</tr>
<tr>
<td>10Ro</td>
<td>47</td>
<td>0.24</td>
<td>0.79</td>
<td>0.51</td>
<td>9.7</td>
</tr>
<tr>
<td>20Ro</td>
<td>23.5</td>
<td>0.12</td>
<td>0.89</td>
<td>0.11</td>
<td>4.2</td>
</tr>
</tbody>
</table>

*Contribution is only from 1st mfp

**Integrating over azimuth between Rx and Rx-Ro

The surface brightness remains substantial out to many times the radius of the nucleus.

The counting rate is then determined by the solid angle the comet subtends at the detector. In order to determine this we consider two mission options: (1) a closest approach of 1000 km and (2) a closest approach of 100 km.

1000 km Approach

At this distance the angle subtended by the nucleus = \( \frac{2 \times 2.5}{1000 \text{ km}} \) \( \approx 0.286^0 \) and the angle subtended by the entire disc of 10 Ro \( \approx 3.18^0 \). The solid angle, dΩ, subtended by the disc of radius 10 Ro = \( \left( \frac{2 \times 10 \text{ Ro}}{1000 \text{ km}} \right)^2 \) = 2.5 x 10^{-3} ster where Ro = 2.5 km.

Taking the effective area of the system to be 20 cm² and taking the average surface brightness of the disc of radius 10 Ro to be about 0.63 that of the nucleus (see data in Table 2-2) the total counting rate of O fluorescence X-rays equals:

\[
2.3 \times 10^2 \text{ counts/sec-cm}^2 \text{-ster x 20 cm}^2 \times 2.5 \times 10^{-3} \times 0.63 = 7.3 \text{ counts/sec}
\]
This counting rate is fairly low but integration times of a few times $10^4$ sec pointed at the comet will result in a substantial number of counts. We repeat the claim that this estimate is probably low because we have neglected the O VIII and O VII lines in the Sun which are very strong and very efficient in producing O lines. Also, other components of the outgoing spectrum have been neglected such as other elemental fluorescent lines and scattered solar X-rays.

Since the principal objective of the investigation is to study the spatial distribution of the X-ray emission of the comet, the $3^\circ$ region that extends a distance 10 Ro around the nucleus should be observed with good spatial resolution. The most effective way to achieve both full coverage and resolution is to use an imaging telescope and an appropriate position sensitive detector. The telescope would be pointed directly at the comet for a period of several hours. It can also be pointed several degrees away from the center of the comet to measure the surface brightness at distances of 20 Ro, 50 Ro, etc. The telescope need only have an effective area of 20 cm$^2$ which would be achieved within a total geometric aperture of 10 cm x 10 cm.

**Chemical Composition**

Determination of chemical composition from the analysis of the X-ray spectrum into characteristic component lines is feasible, although the problem here is more difficult than it was for the Moon from Apollo because the flux is smaller. The technique would be similar, non-dispersive analysis based on the use of balanced filters with pulse height analysis of the detector signals as an aid in separating lines and reducing background. Filters of magnesium and aluminum would be placed over areas of the focal plane covering 25% of the effective area or 5 cm$^2$ (out of a total of 20 cm$^2$) in each case. Since the telescope by focussing concentrates the flux out to a small imaging detector, the filters themselves are actually quite small, amounting to only 9mm x 9mm. In the case of the lunar measurements
from Apollo it took about 30 seconds of observation to obtain meaningful statistics for the Mg, Al, and Si group from a Sun lit area of the Moon. Considerably more time is required here but since spatial resolution in the chemical analysis is not an objective, it is possible to integrate for very long periods of time compared to Apollo to obtain good statistics. Scaling from the Apollo (A) integration time of 30 seconds for each lunar region we obtain for the integration time for the comet (C) mission:

\[ T_{\text{comet}} = T_{\text{Apollo}} \times \frac{(\text{Area})_A}{(\text{Area})_C} \times \frac{(d\Omega)_A}{(d\Omega)_C} \]

\[ (\text{Area})_A = 30 \text{ cm}^2 \quad (d\Omega)_A = 0.5 \text{ ster} \]

\[ (\text{Area})_C = 20 \text{ cm}^2 \quad (d\Omega)_C = \frac{2.5}{4} \times 10^{-3} \text{ ster} \]

\[ T_c = 30 \times \left( \frac{30}{20} \right) \left( \frac{0.5 \times 4 \times 10^3}{2.5} \right) = 3.6 \times 10^4 \text{ sec} \]

That is about 10 hours of integration time would be required to provide the same statistics as for a single lunar region assuming the observations take place when the comet is 1 AU from the Sun.

100 km Approach

At this distance the comet occupies a much larger solid angle. For the nucleus itself:

\[ \Delta \theta = \frac{5}{100} \sim 3^\circ \]

\[ d\Omega = \left( \frac{5}{100} \right)^2 = 2.5 \times 10^{-3} \text{ ster} \]

and the region of radius 10 Ro is 30° in size. The field is too large to use focussing telescopes so the measurements are carried out by using detectors collimated to about 3° and scanning across the comet to map out its mass distribution. Two techniques are possible in this situation: (1) filters in conjunction with separate but co-aligned detecting elements, and (2) a single detector without filters but with superior pulse height resolution. To conserve weight the separate detecting elements of the first technique could actually be a single position sensitive detector similar to but larger in area than the one that would be in the focal plane of the imaging telescope.
The second technique could be based on the recently developed proportional scintillation counter which can be made large in area and whose energy resolution is twice as good as that of a conventional proportional counter.

To estimate the rates we will consider the first technique, several detecting elements plus filters. The total area of the detector is assumed to be \(100 \text{ cm}^2\) with \(30 \text{ cm}^2\) unfiltered and \(25 \text{ cm}^2\) each behind the Mg and Al filter. The rate for the O\(^{6}\) line from a \(3^\circ\) region containing the nucleus is:

\[
2.3 \times 10^2 \frac{\text{counts}}{\text{sec-cm}^2-\text{ster}} \times 50 \text{ cm}^2 \times 2.5 \times 10^{-3} \approx 30 \frac{\text{c}}{\text{sec}}
\]

The rate is lower for off axis locations due to fall off of the surface brightness at larger distances from the nucleus. Assuming that we would like a statistical precision of 1\% in the measurement of the distribution of X-ray intensity with distance from the nucleus, we would need \(10^4\) counts in each angular position or a total time of 5 minutes in each position. Therefore, the mapping of a \(30^\circ\) region could be accomplished easily in a few hours or less. The intensities of the Mg, Al, and Si lines could be measured in the same time by the filtered elements. Scaling to the Apollo measurements, the time required is:

\[
T = 30 \text{ sec} \times \frac{30 \text{ cm}^2}{25 \text{ cm}^2} \times \frac{0.5 \text{ ster}}{2.5 \times 10^{-3} \text{ ster}} = 7200 \text{ sec}
\]
APPENDIX B

COMETARY INSTRUMENTS - SPACECRAFT REQUIREMENTS

Instrument Proposed For 1000 Km. Range

1.0 INSTRUMENT LOCATION (Boom, Scan Platform, Bus)
   1.1 Sensor  Bus
   1.2 Electronics  Bus
   1.3 Separate platform required?  No

2.0 INSTRUMENT MASS AND SIZE
   2.1 Remote from Spacecraft Electronic Bus Compartment  N/A
   2.2 In Spacecraft Electronic Bus Compartment  10.5-Lb. 23.5-In. x 7.5-In. Dia.

3.0 INSTRUMENT POWER
   3.1 How Much?  3 Watts (Operating)
   3.2 What Type?  28+5 VDC (Regulated)

4.0 THERMAL REQUIREMENTS
   4.1 Operating Temperature Limits  0° to +30° C
   4.2 Preferred Temperature  +1° C
   4.3 Non-operating Temperature Range  -30° to 50° C
   4.4 Special Thermal Constraints  TBD
   4.5 Replacement Heaters Required When Instrument Is Not On?  TBD
   4.6 Power Distribution Between Electronics Compartment And Sensor  N/A

5.0 DATA REQUIREMENTS
   5.1 Instrument Modes As A Function Of Mission Phase And Associated Data Rate  420 Bits/Sec
   5.2 Command & Control Requirements  8 Commands
   5.3 Data Storage Requirements  -0-
   5.4 Bit Error Rate Requirements  N/A
### 6.0 ATTITUDE CONTROL AND ARTICULATION

#### 6.1 Sensor Orientation

<table>
<thead>
<tr>
<th>Field of View (if multiple sensors, specify for each)</th>
<th>3° FWHM</th>
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</table>

#### 6.1.2 Preferred Viewing Direction;

At Comet Nucleus

What Angular Range Is Required?

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<th>Preferred Viewing Direction</th>
<th>At Comet Nucleus</th>
</tr>
</thead>
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#### 6.2 Pointing And Stability

<table>
<thead>
<tr>
<th>Pointing Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1° Absolute</td>
</tr>
<tr>
<td>0.02° Knowledge</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Special Requirements</th>
<th>N/A</th>
</tr>
</thead>
</table>

### 7.0 MISCELLANEOUS

#### 7.1 In Flight Calibration Requirements: What And How Often?

Occasional Pointing At Cosmic X-ray Source On Mission Is Desirable.

<table>
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<tr>
<th>In Flight Calibration Requirements</th>
<th>Occasional Pointing At Cosmic X-ray Source On Mission Is Desirable</th>
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</table>

#### 7.2 Special Mission Sequences Requirements.

TBD

<table>
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<tr>
<th>Special Mission Sequences Requirements</th>
<th>TBD</th>
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#### 7.3 Special Instrument Constraints

Solar Avoidance If No Shutter

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<th>Special Instrument Constraints</th>
<th>Solar Avoidance If No Shutter</th>
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#### 7.4 Special Instrument Induced Environment

None

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<thead>
<tr>
<th>Special Instrument Induced Environment</th>
<th>None</th>
</tr>
</thead>
</table>
COMETARY INSTRUMENTS - SPACECRAFT REQUIREMENTS

Instrument Proposed For 100 Km. Range

1.0 INSTRUMENT LOCATION (Boom, Scan Platform, Bus)
1.1 Sensor
   Scan Platform
1.2 Electronics
   Scan Platform
1.3 Separate platform required?
   No

2.0 INSTRUMENT MASS AND SIZE
2.1 Remote From Spacecraft Electronic Bus Compartment
   6.50-Lb.
   6.0-In.x5.0-In. Dia.
2.2 In Spacecraft Electronic Bus Compartment
   N/A

3.0 INSTRUMENT POWER
3.1 How Much?
   3 Watts (Operating)
3.2 What Type?
   28+5 VDC (Regulated)

4.0 THERMAL REQUIREMENTS
4.1 Operating Temperature Limits
   0° to +30° C
4.2 Preferred Temperature
   +10° C
4.3 Non-operating Temperature Range
   -30° to +50° C
4.4 Special Thermal Constraints
   TBD
4.5 Replacement Heaters Required When Instrument Is Not On?
   TBD
4.6 Power Distribution Between Electronics Compartment And Sensor
   28 VDC to Electronics
   28 VDC to Heater

5.0 DATA REQUIREMENTS
5.1 Instrument Modes As A Function Of Mission Phase And Associated Data Rate
   120 Bits/Sec
5.2 Command & Control Requirements
   8 Commands
5.3 Data Storage Requirements
   -0-
5.4 Bit Error Rate Requirements
   N/A
6.0 ATTITUDE CONTROL AND ARTICULATION

6.1 Sensor Orientation

6.1.1 Field of View (if multiple sensors, specify for each)

6.1.2 Preferred Viewing Direction; What Angular Range Is Required?

6.2 Pointing And Stability

6.2.1 Pointing Accuracy

6.2.2 Special Requirements

7.0 MISCELLANEOUS

7.1 In Flight Calibration Requirements: What And How Often?

7.2 Special Mission Sequences Requirements

7.3 Special Instrument Constraints

7.4 Special Instrument Induced Environment