Science & Global Security, 1989, Volume 1, pp.129–146
Photocopying permitted by license only
Reprints available directly from the publisher

Printed in the United States of America

Detection of Space Reactors by their Gamma-ray and Positron Emissions

Joel R. Primack,[a] Philip Pinto,[b] and Oleg F. Prilutsky[c]

A ban on nuclear reactors in orbit could be verified using the tremendous flux of gamma rays and positrons that such reactors emit when operating. Indeed, these radiations already constitute a significant background for orbiting gamma-ray astronomical satellites. In this paper, we estimate the gamma-ray flux from reactors on spacecraft, using the design parameters for the US SP-100 space reactor as an example. We then summarize the sensitivities of several existing and planned gamma-ray detectors. We give special attention to the COMPTEL Compton telescope, one of the four instruments that will be included on the US Gamma Ray Observatory (GRO) satellite, which is scheduled for launch in 1990. We show that the gamma flux from an SP-100 could be detected at thousands of kilometers with COMPTEL, and demonstrate that COMPTEL would typically detect a reactor in low earth orbit several times per day. Finally, we briefly discuss positrons from orbiting reactors both as a signal for verification and as an undesirable background for gamma-ray astronomy.

a. Department of Physics, University of California, Santa Cruz, CA 95064 USA

b. Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138 USA

c. Institute of Space Research of the USSR Academy of Sciences, Profsoyuznaia 88, 117810 Moscow, USSR

This paper was written under the auspices of the Cooperative Research Project on Arms Reductions, a joint project of the Federation of American Scientists and the Committee of Soviet Scientists for Peace and Against the Nuclear Threat

INTRODUCTION: GAMMA RAY FLUX FROM SP-100

Although operating reactors in orbit can readily be detected by observing the infrared radiation emitted by their heat radiators,[1] it is also important to consider detection via nuclear emissions—in particular gamma rays and positrons. These nuclear emissions are relatively easy to detect, and they are clear signals that the power source is a nuclear reactor.

In order to discuss detection of the nuclear emissions from space reactors, we will consider the proposed US space reactor, SP-100, which would have a design power of about 2.5 megawatts thermal and 100 kilowatts electric. The number of fissions per second is directly proportional to the thermal power of the reactor, so for a fixed amount of shielding the nuclear radiation intensity should also scale roughly with the thermal power.

As a starting point, we can take the following SP-100 design parameters:[2]

- Unshielded radiation dose at the inside edge of the radiation shield, 0.3 meters from center of core:

  5×10^{11} rads in 7 years = 2.3×10^{3} rads per second.

- Shielded radiation dose to payload, 25 meters from reactor, shielded by a small tungsten and lithium hydride "shadow shield" at the reactor in the direction of the payload:

  5×10^{5} rads in 7 years = 2.3×10^{-3} rads per second.

In order to estimate the corresponding flux of gamma rays, we use the dose-to-fluence conversion factor[3]

$$1 \text{ rad} = \frac{2.17 \times 10^{9}}{E} \text{ photons per square centimeter}$$

where E is the gamma-ray energy in MeV, and we assume that the gamma rays have a mean energy of 1 MeV. The above numbers then translate into the following equivalent fluxes at 1 meter from the core center:

- Unshielded flux of 1-MeV gamma rays at 1 meter:[4]

  $F_{\text{unshielded}}(1\ \text{m}) = 4.4 \times 10^{11}\ \text{cm}^{-2}\ \text{s}^{-1}$

- Shielded flux of 1-MeV gamma rays at 1 meter:

  $F_{\text{shielded}}(1\ \text{m}) = 3.1 \times 10^{9}\ \text{cm}^{-2}\ \text{s}^{-1}$

The factor by which the SP-100 flux in the direction of the payload is reduced by the shield is given by the ratio[5]

$$\text{shielding factor} = \frac{F_{\text{unshielded}}(1\ \text{m})}{F_{\text{shielded}}(1\ \text{m})} = 1.4 \times 10^{2}.$$

It would be possible to shield such a reactor on all sides, at a cost of several additional tonnes of shielding material (for example, 6 centimeters of lead), to decrease the flux in all directions by about the same factor. Such a shield will be assumed below in discussing the detection of a "shielded" reactor in space.

The space reactor gamma fluxes calculated above are enormously larger than the background fluxes in space and can be detected at considerable distances even with relatively insensitive gamma-ray detectors. Indeed, as is discussed below, gamma rays and positrons from the Soviet RORSAT space reactors have been seen by the gamma-ray spectrometer on the Solar Maximum Mission (SMM) satellite, by the High Energy Astrophysics Observatory (HEAO-C) satellite[6], and by balloon-borne gamma-ray detectors.[7]

The flux falls off with distance R as R^{-2}, so the flux is smaller by a factor of 10^{-6} at 1 kilometer and 10^{-12} at 1,000 kilometers. Since gamma rays are absorbed by the atmosphere, they can be detected only by instruments on spacecraft or high-altitude balloons.

The distance at which the reactor signal is detectable by a particular instrument is determined by the sensitivity as well as other characteristics of the instrument. We will discuss some current and proposed gamma-ray detectors below. Their sensitivity may be summarized as follows: for present detectors using relatively short integration times of a few minutes to a few hours, there is a minimum detectable flux F_m of order 10^{-2}–10^{-4} cm^{-2} s^{-1}, with several orders of magnitude improvement possible using the best available technology and longer integration times.

The main background flux for a space gamma-ray detector typically comes from the activity of the instrument itself in the space environment. This activity is caused by radioactivity in the material from which the detector is constructed. Much of this radioactivity is induced by radiation-belt particles and cosmic rays.

For a Compton telescope, however, the instrumental background is typically smaller than the sky (space) background flux, which for gamma rays of about 1 MeV is[8]

$$F_{sky} \approx 1 \times 10^{-3}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}.$$

Conservatively assuming $F_m = 7 \times 10^{-3}$ cm^{-2} s^{-1} (corresponding to a 5-

Table 1: X-ray and γ-ray Astronomy Satellites that may be Affected by Orbiting Reactors

	Band	Launch by	Date
SMM	γ	US	1980
Exosat	x	ESA*	1985
Mir/Kvant	x,γ	USSR	1986
Ginga	x	Japan	1987
Granat	γ	USSR	1988
Gamma-1	γ	USSR	1989
GRO	γ	US	1990 launch
Rhosat	x, EUV†	ESA	1990 launch
Spectra-X	x	USSR	1992
Axaf	x	US	mid 1990s
BBXRT	x	US	mid 1990s
NAE	γ	US	mid 1990s
Spectra-2	x,γ	USSR	mid 1990s
EUVE	EUV	US	no date set
Spectrosat	x, EUV	ESA	no date set
XTE	x	US	no date set
XMM	x	US	no date set
Hete	x,γ	US	no date set
Grasp	γ	US	no date set
SpEx	x	US	no date set
Astre	x	US	no date set

* European Space Agency
† extreme ultraviolet

Source: G.A. Kriss, "Future Space Instrumentation for Multi-Wavelength Astrophysics," in F. Cordova, ed., *Multi-Wavelength Astrophysics* (Cambridge: Cambridge University Press, 1988).

standard-deviation [5σ] detection with an integration time of about 100 seconds using the Compton telescope COMPTEL on GRO, discussed below), an unshielded SP-100 reactor would be detectable at 8,000 kilometers, and a shielded reactor at 650 kilometers.

The above detection distances would be 10 times smaller for a reactor that had been shut down for one day because the total activity of the fission fragments in a reactor that had been operating for a week or more drops at shutdown to about 7 percent of its operating activity and declines slowly thereafter, reaching about 1 percent after one day.[9]

Therefore, as will be shown in more detail below, a space reactor such as SP-100 can readily be detected by astronomical gamma-ray-detector satellites. Since the US, the USSR, and other countries have either launched such satellites or are planning to launch them soon (see below and table 1), these countries would already have some capability to verify restrictions on orbiting reactors without requiring additional, dedicated gamma-ray satellites.

However, monitoring of a ban on space reactors might add a national security incentive to the purely scientific incentive to develop and put into orbit a new generation of more powerful gamma-ray detectors. In addition, it would be possible, for purposes of redundancy, to include relatively small and inexpensive gamma-ray detectors on several general-purpose satellites launched into a variety of orbits. For example, such gamma-ray detectors might be similar to the SMM Gamma Ray Spectrometer pictured in figure 1.

GAMMA-RAY DETECTORS

Several satellites presently in earth orbit carry gamma-ray detectors, and it is possible that they could be useful in monitoring a ban on reactors in space. For example, the gamma-ray detectors on the VELA early-warning satellite have sensitivities of order 0.1 cm^{-2} s^{-1}.[10] Those on the more modern NAVSTAR satellites are presumably better and are moreover in lower orbits (semi-synchronous with a 12-hour period).

The Gamma Ray Spectrometer on the Solar Maximum Mission (SMM) satellite is pictured in figure 1. It has a minimum detectable flux F_m of about 0.001 cm^{-2} s^{-1} with an integration time of a few hours. It was launched in February 1980 and is still operating (it was repaired by space shuttle astronauts in 1984). It has seen gamma rays and positrons from almost every Soviet RORSAT (radar ocean reconnaissance satellite) operating since 1980.

Tueller et al. from NASA/Goddard, Bell Labs, and Sandia, have an instrument called GRIS (Gamma-ray Imaging Spectrometer). It has seven 200-cubic-centimeter large-area germanium semiconductor detectors with a narrow-line sensitivity of 5×10^{-5} cm^{-2} s^{-1} for an observing time of a few hours. While not incorporated in a satellite, this instrument has flown on high-altitude balloons.

The Gamma Ray Observatory (GRO), planned for space shuttle launch in mid-1990, includes four gamma-ray sensors, of which two may be useful in detecting space reactors: the Oriented Scintillation Spectrometer Experiment (OSSE), which consists of four identical shielded and collimated scintillation detectors with an energy range of 0.1–10 MeV, each gimbal-mounted allowing rotation in a plane, and each with a 3.8° × 10° field of view, and COMPTEL, shown in figure 2, a wide-field-of-view (1 steradian) imaging Compton gamma-ray telescope covering 1–30 MeV and providing 5–8 percent energy resolution and 7.5-arcminute angular resolution (1-σ, strong source).[11] The estimated source sensitivities are 2×10^{-5} cm^{-2} s^{-1} (line) and 3×10^{-5} cm^{-2} s^{-1} (continuum, 0.1–10 MeV) for OSSE, and 3×10^{-6}–3×10^{-5} cm^{-2} s^{-1} (line) and 5×10^{-5} cm^{-2} s^{-1} (continuum, E >

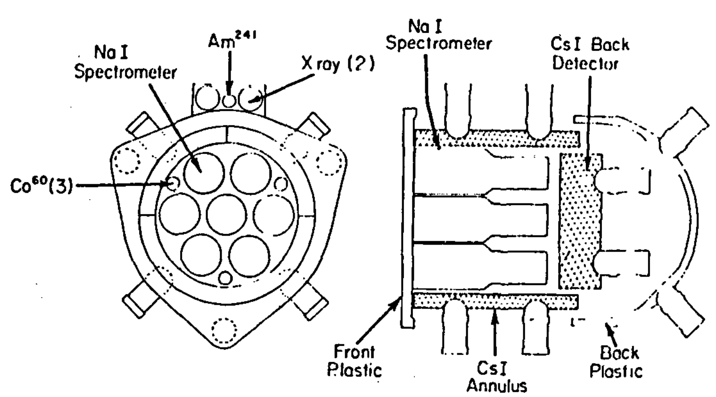

Figure 1: Schematic drawing of the Gamma Ray Spectrometer (GRS) on the Solar Maximum Mission (SMM) satellite, from D.J. Forrest et al., *Solar Physics*, **65**, 15 (1980). The heart of the GRS is seven sodium iodide (NaI) detectors, operating as a spectrometer between 0.3 and 0.9 MeV. Their sensitivity is calibrated in flight using small radioactive sources. The NaI detectors are surrounded by cesium iodide and plastic scintillators, which act as an active anticoincidence shield; the signals in the NaI detectors are ignored if charged particles are seen at the same time by these surrounding detectors.

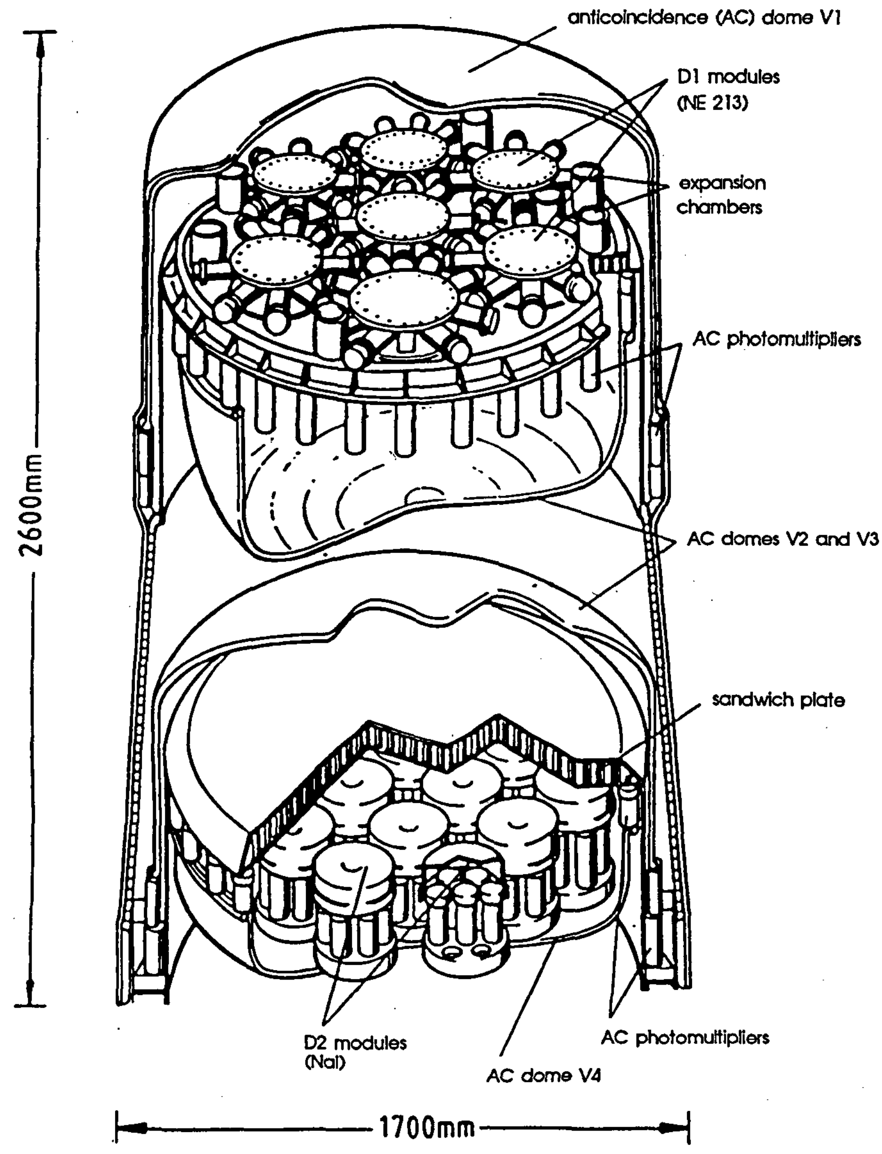

Figure 2: Schematic drawing of the imaging Compton telescope (COMPTEL) on Gamma Ray Observatory (GRO), from *The Gamma-Ray Observatory Science Plan*, prepared by Gamma-Ray Observatory Science Working Team, D. Kniffen, chairman (revised January 1988). The upper detector consists of seven cylindrical modules of liquid scintillator NE 213, the lower detector consists of 14 blocks of NaI, each viewed by photomultipliers. Each is entirely surrounded by an anticoincidence shield. COMPTEL *also has the ability to image sources of neutrons.*

1 MeV) for COMPTEL. (The quoted sensitivities are for observing times of about a month.) In addition, the GRO Burst and Transient Source Experiment (BATSE) will detect positrons from orbiting reactors. Indeed, these positrons could be a very deleterious background for GRO, as will be seen below.

The proposed Nuclear Astrophysics Explorer (NAE) is a small and relatively inexpensive (about $80,000,000) satellite whose design uses sophisticated technology. Its gamma-ray detector achieves a high angular resolution of $\Delta\theta \approx 2°$ with a 10° or 1° (selectable) field of view using a coded mask[12], and it has a very good energy resolution of $\Delta E \approx 1$ keV. It has a high-energy-resolution sensitivity $F_m \approx 3 \times 10^{-6}$ cm^{-2} s^{-1} with an integration time of 10^6 seconds (about 10 days), and $F_m \approx 3 \times 10^{-4}$ cm^{-2} s^{-1} in 30 minutes.

The Advanced Nuclear Gamma-ray Analysis System (ANGAS) is being designed by Lockheed Palo Alto for the Defense Advanced Projects Research Agency (DARPA). It is planned to be flown in 1991 on a dedicated US Air Force satellite, *P86-2*, and is designed to operate for 3.5 years. It will be at least as sensitive as the NAE, and will probably be used to observe sources of gamma radiation in orbit.

Sadoulet et al.[13] have proposed to NASA the construction of an advanced double-Compton gamma-ray telescope called High Energy All Sky Imager (HEASI), incorporating a high-pressure drift chamber that would allow high precision (< 1 millimeter) measurement of the Compton scattering position as well as measurement of the direction of the scattered electron. Its angular resolution for 1-MeV gammas remarkably would be a few arcminutes for each event, with energy resolution of order 1 percent, and its sensitivity would be of order 10^{-8} cm^{-2} s^{-1} with long integration times (months).

Cline et al.[14] have proposed a very large Compton telescope gamma-ray detector with a liquid argon converter and calorimeter separated by a methane gas drift chamber. This device, which in its largest form has been proposed for space station deployment, could achieve a sensitivity of perhaps 10^{-9} cm^{-2} s^{-1} with long integration times.

These last proposals are an indication of the sensitivities that may be possible with the best current technology.

The same sorts of gamma-ray detectors that scientists are planning for astrophysical observations would obviously be excellent devices to verify the proposed ban on reactors in orbit. Furthermore, it is likely that any satellite put up to verify such a ban would produce data of astrophysical importance. This is what happened with the VELA satellites, which were put up to monitor the Limited Test Ban Treaty of 1963, but then discovered gamma-ray burst sources.[15]

CALCULATION OF THE MINIMUM DETECTABLE FLUX F_m FOR THE COMPTEL TELESCOPE

For a reactor in space to be detected, its signal must compete with both the cosmic and instrument background rates. A Compton telescope detects both the location and energy deposited on the electron in the initial Compton scattering ($e + \gamma \rightarrow e + \gamma$, where e is an electron in the upper scintillator, and γ is the gamma ray photon) and also the location and energy of the scattered photon in the lower scintillator (calorimeter).[16]

This information restricts the possible direction of the detected incident photons to a circular annulus (ring) on the sky. Since many gamma rays will arrive from a bright source, the direction of that source can be pinpointed as the overlap of these annuli.

By requiring coincident measuring of a Compton scattering and the absorption of the scattered photon, a Compton telescope achieves low background and fairly high resolution and sensitivity without the use of collimators or masks. For COMPTEL, the veto shielding against charged particles around both the upper and lower scintillators reduces the instrument background so much that it is always less than the cosmic background flux. The minimum detectable flux is then given by the following formula:[17]

$$F_m \approx m(I_c \Delta E \Delta\Omega / At)^{1/2} \approx 7 \times 10^{-3}\ t_2^{-1/2}\ \text{cm}^{-2}\ \text{s}^{-1}$$

where

I_c = cosmic background $\approx 10^{-2}$ cm^{-2} s^{-1} sr^{-1} MeV^{-1} at 1 MeV
ΔE = energy band of detector, taken here to be 1 MeV
$\Delta\Omega$ = 1σ angular resolution element $\approx$ 0.4 sr at 1 MeV
A = effective area of detector $\approx$ 20 cm^2 at 1 MeV

t = observation time
t_2 = t in hundreds of seconds
m = number of σ detection criterion, taken here to be 5.

COMPTEL DETECTION OF GAMMA RAYS FROM SP-100

For simplicity, we will consider placing reactors in only two possible orbits: low earth orbit (LEO) at, say, 400 kilometers and geosynchronous orbit (GEO) at about 40,000 kilometers. Since the atmosphere is a bright source of gamma rays and detectors should stay below the Van Allen radiation belts to decrease instrumental backgrounds, we will consider only gamma-ray detectors in LEO looking upward and sideways.

If an unshielded SP-100 reactor were in GEO, it would be above the horizon whenever a detector satellite in LEO was on the same side of the earth. COMPTEL could detect it in about one day (about 10^5 seconds) of integration time, corresponding to a few days of observation. However, if the reactor were shielded, detection by COMPTEL would be marginal at best.

However, a shielded reactor in GEO could be detected in LEO by the more sensitive gamma-ray detectors currently being developed (see above), or by a gamma-ray detector on a spacecraft in high orbit that was able to maneuver so that it could come within a few thousand kilometers of the suspected reactor.

Typical of LEO satellite geometry is the following: at an altitude of 400 kilometers looking at another satellite at the same altitude, the maximum line of sight above the atmosphere (100 kilometers above the earth's surface) would be 4,000 kilometers.

Let us define an "encounter" between a detector and another satellite as occurring when they come within a distance $d_3 \times 10^3$ kilometers of each other. (d_3 is just the distance in units of 1,000 kilometers. In our example, we have taken the maximum value of d_3 to be 4.) Then, by the sort of reasoning employed in standard mean-free-path calculations,[18] the number of encounters closer than d_3 per day for two satellites in random[19] LEO orbits (distance from the center of the earth $R \approx 7000$ kilometers with 16 orbits per day) is given by

$$\frac{\text{area swept out per orbit}}{4\pi R^2} \times \frac{16 \text{ orbits}}{\text{day}} = \frac{2d_3\ 10^3 \text{ km} \times 2\pi R \times 16}{4\pi R^2} \approx 2d_3.$$

This results in about 8 encounters per day in our example if $d_3 = 4$. The integration time per encounter at orbital velocities of 8.3 kilometers per second is of order $100d_3$ seconds.

For an unshielded SP-100, the ratio of the flux $I_{\text{SP-100}}$ to the minimum detectable flux is then

$$\frac{I_{\text{SP-100}unshielded}}{F_m} \approx \frac{4.4 \times 10^{-1} d_3^{-2}}{7 \times 10^{-3} d_3^{-1/2}} \approx 60 d_3^{-3/2},$$

where the relation $t_2 \approx d_3$ is used to express F_m, for a relative encounter velocity of order 10 kilometers per second. Thus each of the approximately eight encounters per day within a line-of-sight distance of 4,000 kilometers ($d_3 \leq 4$) will be a clear detection.

For a shielded SP-100,

$$\frac{I_{\text{SP-100}shielded}}{F_m} = \frac{3.1 \times 10^{-3} d_3^{-2}}{7 \times 10^{-3} d_3^{-1/2}} \approx 0.4 d_3^{-3/2}.$$

Since this requires $d_3 \leq 0.4^{2/3} \approx 0.5$ for detection, there will be about one detection per day.

In either case, it is clear that a few COMPTEL-type detectors in appropriate low orbits would suffice for rapid and sure detection of a reactor in low orbit with the power of an SP-100.

POSITRON AND GAMMA-RAY "POLLUTION"

The main physical mechanism for absorption of gamma rays with energy greater than about 2 MeV passing through matter is pair production, in which a gamma ray is converted into an electron and a positron near a nucleus. When this happens in the outer shell of a spacecraft containing a reactor, the electrons and positrons can escape into space. They are then trapped in the earth's magnetic field, bouncing back and forth along field lines and effectively becoming an artificial radiation belt until they are removed by collisions with atoms in the upper atmosphere.

The electrons are relatively harmless, but the positrons are of great concern for gamma-ray astronomy because when a positron strikes an atom it annihilates an electron, and two 511-keV gamma rays are usually emitted. If this happens in the skin of a spacecraft that passes through the positron cloud, and the spacecraft contains a gamma-ray detector, these annihilation gamma rays would constitute an unwanted background—unless the purpose of the detector is to look for orbiting reactors.

The SMM Gamma Ray Spectrometer (GRS) has detected the gamma rays emitted directly from RORSATs as well as the positrons they injected into the earth's magnetic field by every RORSAT launched since 1980.[20] The RORSATs typically cross the same lines of the earth's magnetic field (L shell[21]) at high latitudes as the SMM traverses at lower latitude but higher altitude. (RORSATs are normally launched into orbits of 65° inclination with respect to the equator and 250 kilometers altitude. SMM's inclination is 28° and its altitude, 560 kilometers at launch, had, of 1988, decayed to 480 kilometers.) The positrons are usually detected several minutes after they are emitted, sometimes after having drifted to the other side of the earth.

During 1980–86 there were about five such detections per month, but in 1987–88 the frequency increased to about 250 per month. This tremendous increase coincided with the launch of two new Soviet reactors into orbits of about 800 kilometers altitude, each with roughly twice the electrical power output of the RORSAT reactors.[22] The higher altitude of positron injection apparently greatly increased the positron lifetime in the ionosphere.

The gamma rays from positron annihilation interfered with astronomical observation by the SMM GRS about 5 percent of the time. The gamma-ray burst detector on the Japanese *Ginga* satellite fills the storage capacity of its on-board memory until the data can be telemetered to its ground station—which can be from one to four orbits later; this instrument was blinded about 20 percent of the time.[23]

We will now make a very rough estimate of the flux of positrons from a reactor detected by SMM. First, the number of gamma rays emitted per second with energy more than about 1.5 MeV is roughly 1×10^{16}, assuming the RORSAT reactor operates at a thermal power level of 100 kilowatts and scaling to the number in endnote 4.

Assuming an attenuation factor of 30 for the gamma flux in passing through the reactor, and another factor of 1,000 reduction for the possibility that an outgoing gamma ray will produce a positron within its approximately 1-millimeter escape range from a satellite surface,[24] the net number of positrons emitted and captured by the earth's magnetic field per second, $\dot{N}_+$, is approximately 3×10^{11}.

These positrons bounce back and forth along the magnetic field lines in a given L shell and drift in longitude with a velocity v_d of the order of 10^5 centimeters per second[25] and a lifetime t; they are injected by a spacecraft with orbital velocity $v_{orb} \approx 7 \times 10^5$ centimeters per second. Thus the volume $V(t)$ in which positrons are confined, setting the length of the field lines approximately equal to the radius of the earth R_E and neglecting angular factors, is very roughly

$$V(t) \approx R_E(v_{orb}t)(v_d t).$$

The number of positrons $N^+(t)$ injected into this volume is about $t\dot{N}_+$, so it follows that their number density n_+ is approximately

$$n_+ = \frac{N_+(t)}{V(t)} \approx \frac{\dot{N}_+}{R_E v_{orb} v_d t} \approx \frac{3 \times 10^{11}}{(6.4 \times 10^8)(7 \times 10^5)10^5 t} \approx 7 \times 10^{-9}\ t^{-1}\ \text{cm}^{-3}\ \text{s}.$$

The corresponding flux of positrons is

$$F_+ \approx cn_+ \approx 200\ t^{-1}\ \text{cm}^{-2}$$

where c is the speed of light. For example, this would give a (rather large) detected flux of 0.2 $\text{cm}^{-2}\ \text{s}^{-1}$ after 10^3 seconds, consistent with the fact that SMM has observed positrons many minutes after emission. A more accurate calculation would have to take into account the depletion of positrons by annihilation, especially for low-altitude injection.

The emission of gamma rays and positrons by orbiting reactors will thus have increasingly deleterious effects on gamma-ray astronomy as the detectors become more sensitive and the reactors become more numerous and powerful. The greatly increased interference from the new Soviet reactors observed by the SMM GRS shows that reactors in 800-kilometer orbits are far worse for gamma-ray astronomy than reactors in lower orbits, although reactors at higher altitudes are less likely to re-enter because higher orbits are more stable. All the x-ray and gamma-ray detectors listed in table 1 are likely to be adversely affected, with the possible exception of the Exosat and Granat satellites, which have high orbits. The worst effect on Gamma Ray Observatory will be on the Burst and Transient Source Experiment (BATSE), which can be effectively blinded for the duration of an orbit once its data storage capacity is reached. The GRO team is working on possible remedies, such as placing it in standby mode when it is likely to encounter a RORSAT or positron cloud.

On the other hand, the positrons provide another signal useful for verifying an agreement banning such reactors. It will be possible to analyze the effectiveness of this method when the observational data is declassified and published.

ACKNOWLEDGMENTS

We are indebted to Seath Ahrens, Dieter Hartmann, Richard Lingenfelter, Jim Matteson, Tom Morgan, and Roy Woodruff for discussions, to Ed Chupp and Jim Kurfess for their public presentations at the UCLA Conference on High Resolution Gamma Ray Cosmology, 4 November 1988, and to David Hafemeister, Ted Taylor, Frank von Hippel, and especially Robert Mozley for very helpful criticism of previous drafts.

NOTES AND REFERENCES

1. David W. Hafemeister, "Infrared Monitoring of Nuclear Power in Space," *Science & Global Security*, this issue.

2. *SP-100 Program Ground Engineering System (GES) Baseline Design Study, Final Report* (Philadelphia, Pennsylvania: General Electric Space Systems Division, 30 November 1984) Document number 84SDS4272. Regarding the shielded flux, the stated dose of 5×10^5 rad at the payload distance of 25 meters comes from table 3.1-3. The unshielded flux at 0.3 meters from the core center was read off figure 3.1-13 (b).

3. The 1972 edition of the American Institute of Physics *Handbook*, p.8-305, gives the dose-to-fluence conversion factor 1 rad = $(2.17 \times 10^9)/E$ photons per square centimeter (with the photon energy E in MeV) in soft tissue.

4. It may be useful to compare this to a first-principles flux estimate. About 7 MeV per fission is emitted in prompt gamma rays and another 7 MeV over time thereafter in gamma rays from the fission fragments. (T. Gozani, *Active Non-destructive Assay of Nuclear Materials*, Nuclear Regulatory Commission Report NUREG/CR-0602, pp.193–200.) In each case, the average gamma energy is about 1 MeV. Altogether, there are a total of about 6 gamma rays per fission (including those from fragments) with energies in the range 0.5–1.5 MeV. Each fission releases about 200 MeV, or 3×10^{-11} joules. Thus the SP-100 design power of 2.5 megawatts thermal corresponds to about 8×10^{16} fissions per second, or about 5×10^{17} gamma rays per second in the 0.5–1.5 MeV energy range. (There are, for example, about 2×10^{17} gamma rays per second in the 1.5–4 MeV energy range.) The corresponding flux at 1 meter is

$$\frac{5 \times 10^{17}\ \mathrm{s}^{-1}}{4\pi \times 10^{4}\ \mathrm{cm}^{2}} = 4 \times 10^{12}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}.$$

The fact that the design flux discussed above is about a tenth this figure is roughly consistent with expected absorption (self-shielding) in the reactor core, supporting structure, and envelope.

5. The reason that the above shielding factor is not 3.5×10^{3}, as claimed by the design report (*SP-100 Report*, 1984), is presumably that the latter factor includes about an order of magnitude geometric decrease in the flux from the inside to the outside of the shield.

6. Private communications from Richard Lingenfelter and Jim Matteson of University of California, San Diego.

7. cf. Terrence J. O'Neill et al., "Observations of Nuclear Reactors on Satellites with a Balloon-Borne Gamma-Ray Telescope," *Science* **244**, 30, 28 April 1989, p.451.

8. J.I. Trombka and C.E. Fichtel, "Gamma-Ray Astrophysics," *Physics Reports* **97** (1983), p.173, esp. figure 2.5.

9. See, for example, A.V. Nero Jr., *A Guidebook to Nuclear Reactors* (Berkeley, California: University of California Press, 1979), p.54.

10. See, for example, I.B. Strong et al., *Astrophysical Journal Letters* **188**, L1 (1974).

11. V. Schönfelder et al., *IEEE Transactions on Nuclear Science* NS-31 (1984), p.766.

12. A coded-mask detector has a grid of absorbers of varying thicknesses in front of it. A strong source will then throw the shadow of this mask onto the detector, and the location of the source can be determined by the location of the shadow.

13. Bernard Sadoulet et al., "High Energy All Sky Imager (HEASI) Explorer," proposal to NASA from Space Sciences Laboratory, University of California, Berkeley, UCBSSL 1304/86, 30 July 1986.

14. David B. Cline (now at UCLA) et al., "Search for Relic Cold Dark Matter with a New Concept in Gamma Ray Telescopes" (Madison, Wisconsin: University of Wisconsin, Physics Department, 1986).

15. See Strong (1974).

16. On the physical principles of Compton telescopes and other gamma-ray detectors, see Rodney Hillier, *Gamma Ray Astronomy* (Oxford: Oxford University Press, 1984), especially chapter 5; also Poolla V. Ramana Murthy and Arnold W. Wolfendale, *Gamma-ray Astronomy* (Cambridge: Cambridge University Press, 1986).

17. Adapted from V. Schönfelder, "Measurement of 1-30 MeV Celestial Gamma Rays with an Imaging Compton Telescope COMPTEL," Proposal for a GRO Experiment (Garching, West Germany: Max-Planck-Institut für Extraterrestriche Physik, 3 February 1978), appendix A.1.

18. See, for example, James Jeans, *An Introduction to the Kinetic Theory of Gases* (Cambridge: Cambridge University Press, 1959), esp. chapter 5. This topic is treated in all textbooks on statistical physics; for example, C. Kittel and H. Kroemer, *Thermal Physics*, second edition (San Francisco, California: Freeman, 1980), p.395.

19. How appropriate is the assumption of random orbits? Although detection by a single orbiting detector could be evaded for a time by judicious choice of the reactor orbit, orbital precession rates, due to effects such as the oblateness of the earth, are typically several degrees per day, depending on the orbital altitude and inclination. Moreover, a dedicated gamma-ray verification satellite would require relatively little rocket fuel to control its own precession. Especially in view of the positron signal, rapid detection could be assured if several gamma-ray detectors in different orbits are available, as will probably eventually be the case if only for astronomical purposes. In the unclassified literature, the problem of orbital encounters has been discussed in the context of collisions between natural objects in the solar system (see Ernst J. Öpik, *Interplanetary Encounters: Close-Range Gravitational Interactions* [Amsterdam, Netherlands: Elsevier Scientific Pub. Co., 1976], esp. chapter 2, "Orbital Encounters"; D. J. Kessler, *Icarus* 48, 39, 1981) and

between earth satellites and space debris (see for example Nicholas L. Johnson and Darren S. McKnight, *Artificial Space Debris* [Malabar, Florida: Orbit Book Co., 1987] and references therein).

20. Most of the information in this section is from talks by Ed Chupp and James Kurfess at the Conference on High Resolution Gamma Ray Cosmology, UCLA, 4 November 1988. They and their SMM-GRS colleagues are preparing papers on this for publication, but at this writing the only unclassified document on the space reactor positron problem is a NASA memo, "Transient Gamma Ray Events," by Arthur J. Reetz, Gamma Ray Observatory program manager, 29 August 1988. *Note added in proof:* The following papers appeared in *Science* **244**, 28 April 1989: E. Rieger et al. "Man-Made Transients Observed by the Gamma-Ray Spectrometer on the Solar Maximum Mission Satellite"; G. Share et al. "Geomagnetic Origin for Transient Particle Events from Nuclear-Reactor Powered Satellites"; and E.W. Hones and P. R. Higbie, "Distribution and Detection of Positrons from an Orbiting Nuclear Reactor." Welcome as these papers are, they include only enough detailed discussion of the observational data to convince the reader that the SMM 511-keV signals were indeed caused by positrons from Soviet reactors. In the same issue there is a report by T.J. O'Neill et al. ("Observations of Nuclear Reactors on Satellites with a Balloon-Borne Gamma-Ray Telescope") of a remarkable brief balloon flight in April 1988 during which a sensitive Compton telescope saw clear gamma-ray signals of four orbiting Soviet reactors—two RORSATs and the two new reactors in higher orbits.

21. The L value at a magnetic field line is the altitude (expressed in multiples of the earth's radius) above the magnetic center of the earth of the equatorial crossing point of that field line. Charged particles spread longitudinally from one magnetic line to another with the same L value, thus forming "L-shell" radiation belts. See, for example, Francis S. Johnson, ed., *Satellite Environment Handbook* (Stanford, California: Stanford University Press, 1965), p.61. Another useful reference is J.A. Ratcliffe, *An Introduction to the Ionosphere and Magnetosphere* (Cambridge: Cambridge University Press, 1972).

22. See Steven Aftergood, "Background on Space Nuclear Power," *Science and Global Security*, this issue.

23. See footnote 24 of Joel R. Primack et al., "Space Reactor Arms Control: Overview," *Science and Global Security*, this issue.

24. Assuming the spacecraft's skin is aluminum. See Samuel Glasstone and Alexander Sesonske, *Nuclear Reactor Engineering* (New York, New York: Van Nostrand Reinhold, 1967) pp.46,53.

25. $v_d \approx rv/R$, where r is the radius of the orbit of the positron around the magnetic field ($\approx$ 100 meters), R is the distance from the center of the earth's magnetic field ($\approx 7 \times 10^6$ meters), and v is the velocity of the positron, which is near the velocity of light, 3×10^8 meters per second.