FURTHER EVIDENCE FOR THE EXISTENCE OF GALACTIC X RAYS*

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(Received 26 September 1963)

In a previous Letter[1] we reported experimental evidence for the existence of x-ray sources outside the solar system. We have since performed two rocket experiments, using similar instrumentation, from the White Sands Missile Range, New Mexico, in October 1962 and June 1963. These flights have furnished additional evidence supporting our interpretation of the earlier data.

The June 1963 flight took place at 23:15 MST on the tenth of the month when the galactic equator crossed the sky from the northeast to the south, with the center of the galaxy in the south. The rocket reached a peak altitude of 229 km and was above 80 km (where the residual atmosphere has a mass of 10 mg/cm^2) for a total of 360 seconds. The rocket spun at a rate of 1.67 rps around its longitudinal axis and precessed with a half-angle of 11° and a period of 84 seconds about an axis which remained relatively fixed during the flight, and which was located about 7° northwest of the local zenith. The instrumentation on board included three Geiger counters, each with windows totaling 20 cm^2 of 50-micron beryllium and a filling gas of 570 mm of argon. The effective window area (corrected for insensitive regions of the Geiger-counter volume arising from electrode design) was about 10 cm^2. An anticoincidence arrangement, similar to that used in the June 1962 flight, greatly reduced the cosmic-ray background. The Geiger-counter axis (i.e., the normal to the windows) made an angle of 70° with the rocket axis. The field of view of the Geiger counters was only limited by the shadow of the nose cone for angles greater than 45° from the normal. One counter functioned correctly throughout the flight, while the other two shifted out of the plateau region. Only data from the functioning counter are presented here. The instrumentation also included two thin scintillation detectors, one with a 1.0-mm thick NaI(Tl) crystal, the other with a 0.78-mm thick anthracene crystal. The anthracene detector was covered with 5 microns of aluminum and was provided with collimators limiting the angle of incidence of a maximum of 20°. The (area) ×(solid angle) factor for this detector was 1.6 cm^2 sr for low-energy particles and increased to 110 cm^2 sr for cosmic rays. Aspect was determined from a combination of optical sensors and flux gate magnetometers.

Each rotation of the rocket was divided into 60 equal intervals beginning at the instant when the normal of the optical sensor (i.e., the vector defining the direction of maximum sensitivity) came closest to the moon-direction vector, and the number of counts occurring in each of these intervals was recorded separately. The data accumulated in this manner by the Geiger counter while the rocket was above 80 km are shown in Fig. 1. The total number of counts recorded above 80 km was 34 827. Because of the precession of the rocket during the flight, the normal to the Geiger counter did not return to the same direction of the sky after each full rotation of the rocket. This, however, did not substantially af-

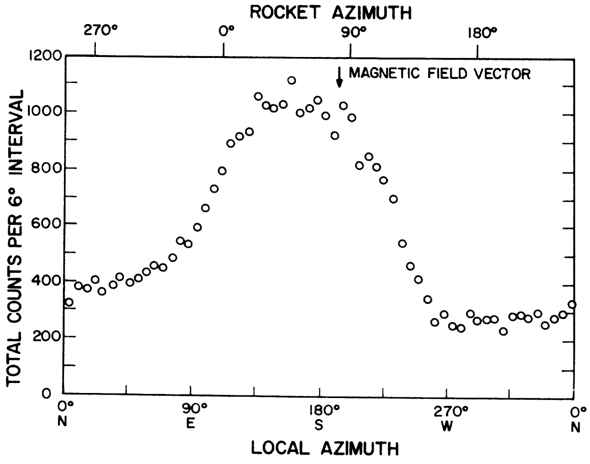

FIG. 1. Accumulated counts as a function of azimuth, June 1963. The upper scale is rocket azimuth of the aspect sensor measured from the moon position. The lower scale is the local azimuth measured from north computed on the assumption that the rocket axis coincided with the axis of the precession cone.

fect the observed azimuthal dependence of the counting rate because the angle of acceptance of the detector was considerably greater than the half-angle of the precession cone. Therefore, in this preliminary analysis, we have neglected the precession and assumed that the spin axis of the rocket was fixed in space and coincident with its average position, i.e., with the axis of the precession cone. Thus the abscissa in Fig. 1 is the azimuth relative to this axis, measured from local north, and computed under the above assumption. As in the June 1962 experiment, the azimuthal variation of the counting rate revealed a strong anistropy, with a peak in the local south that fell off more gradually to the east than to the west.

None of the data obtained with the NaI(Tl) detector, and only a small portion of the data obtained with the anthracene detector, have been analyzed in detail thus far. The recorded pulse-height output of these detectors was an approximately linear function of the energy loss in the crystal up to 80-keV energy losses. Larger energy depositions rapidly saturated the recording system and appear as constant-amplitude pulses. (A minimum ionizing particle would lose 200-keV energy in traversing the anthracene crystal.)

At high altitudes, the anthracene detector was found to record pulses corresponding to energy depositions between 10 keV and 80 keV at a rate of about 9.5 per second (with most of the pulses occurring near the lower limit). These may be produced by photons, by electrons in the 30- to 100-keV range, or by protons in the 1.0- to 1.1-MeV range. Energy loss in the aluminum foil has been considered in evaluating the above energies. The flux of electrons or protons corresponding to the observed counting rate is 5.9 cm^{-2} sec^{-1} sr^{-1}. Pulses corresponding to energy depositions greater than 80 keV were recorded at a rate of about 17 sec^{-1}. These pulses are probably due to a great extent to cosmic rays since the same counting rate is observed at altitudes below 80 km and above the Pfotzer maximum. Assuming them to be all cosmic rays, the flux corresponding to the observed counting rate is 0.16 cm^{-2} sec^{-1} sr^{-1}, which is consistent with the known cosmic-ray flux.

The October 1962 flight took place at 23:59 MST on the twelfth of the month, when the galactic equator was almost directly overhead along an east-west line, and the galactic center was below the local horizon. The rocket reached a peak altitude of 231 km and was above 80 km for a total of 364 seconds. The rocket spun at a rate of 2.0 rps, and the longitudinal axis precessed with a half-angle of 12° around an axis pointed only a few degrees away from the local zenith. The instrumentation included a Geiger counter with a window of 20 cm^2 of 50-micron beryllium, and filling gas of 315 mm of neon and 59 mm argon. The effective window area was 10 cm^2. The Geiger-counter axis made an angle of 55° with the rocket axis. We analyzed the data from this flight in the manner described for the June 1963 flight. The azimuthal variation of the counting rate is presented in Fig. 2 and shows slight peaks in the local east and west. The total number of counts recorded above 80 km was 10 065.

In all three flights, we found that the radiation detected at all orientations of the Geiger counters underwent strong attenuation in the first several mg/cm^2 of atmosphere. From the counting rates in the Geiger counters below 80 km and above the Pfotzer maximum, we estimated an upper limit of 2.6 counts per second for the background rate due to cosmic rays not eliminated by the anticoincidence device. This is only 4% of the peak rate observed in June 1962 and 1.3% of that observed in June 1963.

The outstanding feature of the three experiments is the pronounced peak of intensity observed during the two June flights, and the absence of such a peak in the October flight when a much different region of the sky was in view. For a more detailed comparison of the three experiments, we refer to Fig. 3. The orientations of the axes of precession of each of the three rockets are shown by the circled dots marked

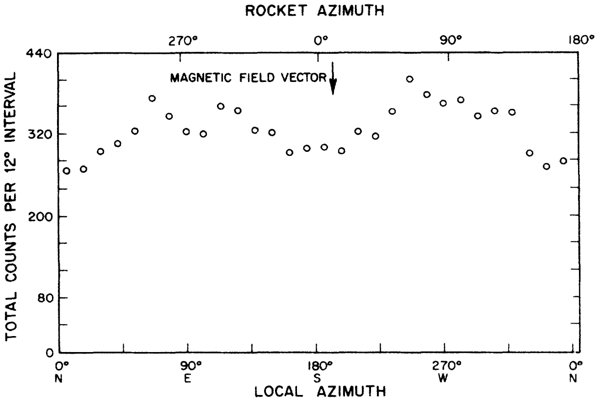

FIG. 2. Accumulated counts as a function of azimuth, October 1962. A description of the scales is given in the caption of Fig. 1.

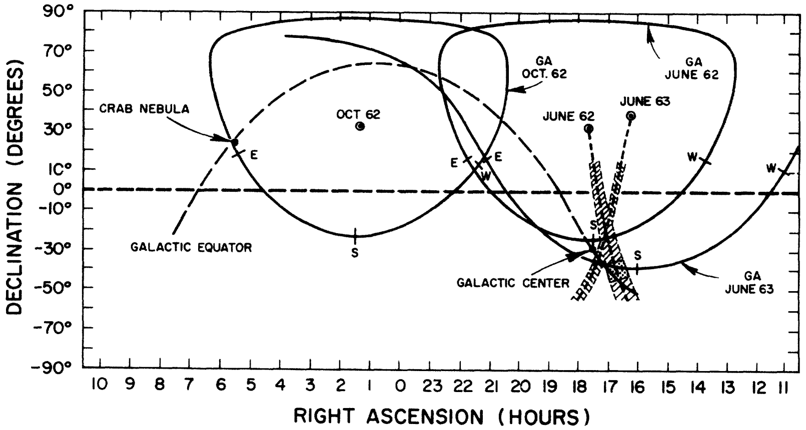

FIG. 3. Chart showing the regions of the sky explored by the counters and the orientations of the rocket axes.

June 1962, October 1962, and June 1963. The solid curves marked GA are the traces of the Geiger counter axes, computed under the approximation that the spin axis of the rocket coincided in each case with the precession axis. These curves are marked E, S, W to indicate local east, south, and west. Because of their broad field of view, the counters were sensitive to x radiation coming from a region of the sky extending from about 20° off the rocket axis to the local horizon. The rocket axes in the 1962 and 1963 June firings were separated by 1 hour 30 minutes of right ascension, and the respective intensity peaks were observed at 193° and 168° local aximuth. These aximuths define arcs of great circles, shown in Fig. 3 by dashed lines. In each case, the source of the radiation responsible for the peak must lie within a band around the corresponding great circle, extending from 20° off the rocket axis to the horizon—the width of the band being determined by the statistical errors of the data and those introduced by the precession of the rockets. These bands, shown by the shaded areas in Fig. 3, intersect over an area which is close to the region of the celestial sphere where the source had been located in the basis of the June 1962 flight alone (the dotted square in Fig. 3). Thus, the two June flights are consistent with a unique celestial location of the source. This fact, and the fact that the source was not observed in October, are strong arguments in favor of the assumption that the radiation responsible for the peaks originates from the galaxy rather than from the earth's upper atmosphere or from any other source within the solar system. They are also arguments in favor of the electromagnetic nature of the radiation, because terrestrial and extraterrestrial magnetic fields would not allow a soft corpuscular radiation from a celestial source to arive at the earth from a fixed direction in the sky.

We have further independent evidence against the possibility that the radiation responsible for the peak may consist of charged particles or of x rays of atmospheric origin. With regard to charged particles, we note in the first place that electrons and protons capable of traversing the Geiger counter windows in the June 1963 flight must have energies in excess of 80 keV and 2 MeV, respectively. From the counting rate of the anthracene counter, we find that such particles could not have contributed more than a few percent of the peak flux recorded by the Geiger counter. Electrons with less than 80-keV energy may be detected by the Geiger counter via bremsstrahlung in the window. The efficiency, however, is very small and decreases rapidly with decreasing energy. From the scintillation counter data we know that electrons with energy from 30 keV to 80 keV could not have made any appreciable contribution to the counting rate of the Geiger counter. There remains the distant possibility of a very large flux of electrons with less than 30-keV energy, to which the scintillation counter was not sensitive. These electrons have a radius of gyration of less than 10 meters in the earth's magnetic field (0.5 gauss at the location of the rocket). Thus they wind in very tight spirals around the field lines, and their flux must exhibit axial symmetry with respect to the magnetic field. Whereas in the June 1962 flight, the azimuth of the peak was nearly coincident with the azimuth of the magnetic field vector, this is clearly not the case in the June 1963 flight. We thus conclude that the radiation responsible for the peak cannot consist of charged particles.

With regard to atmospheric x rays, we recall that the results of the June 1962 flight had already placed a lower limit of 400 km to the altitude of the source above the earth's surface.[1] We are now in a position to increase this lower limit. In the June 1963 flight, because of the precession of the spin axis, the elevation angle α of the normal to the Geiger counter at the azimuth of the source changed periodically from about 10° to about 30°. We found that the counting rate (considered over an azimuthal interval of ±30° with respect to the azimuth of the peak) increased significantly with increasing α. The average counting rate during the time when $30° > \alpha > 20°$ was $9.6 \pm 1.7\%$ in excess of that recorded during the time when $20° > \alpha > 10°$. This means that the elevation of the source was significantly greater than 20°. Furthermore, we have obtained a measure of the minimum distance of the source from the site of the rocket launch from the following considerations. Within statistics, the counting rate averaged over the precession cycle remained constant while the rocket was above 100 km, even though the rocket traveled almost due north (i.e., away from the source) for a distance of 75 km during this time. If we allow for an uncertainty of three times the statistical error, we conclude that the source could not have been closer than 2000 km. This, combined with the elevation estimate, places the source at least 1000 km above the surface of the earth. Thus the earth's lower atmosphere is eliminated as the place of origin of the observed peak of radiation, and the possibility of finding a well-localized source of x rays near the earth at the required altitude appears exceedingly remote.

On the strength of the above evidence, we consider the existence of a localized galactic source of x rays as clearly established (we shall refer to it as source No. 1 in the rest of this paper).[2] However, it is equally clear that this source cannot account for the soft radiation observed in the October flight or for that recorded in the two June flights at large azimuthal angles from the peaks (see Fig. 3).

With regard to the nature of the radiation other than that recorded at the main peak, we note the following. The flux increased markedly as the rocket moved from 80 to 100 km, but then remained approximately constant. This is easily understandable if the radiation consists of soft x rays because the air layer between 80 and 100 km accounts for 98% of the residual atmosphere above 80 km. If, however, the radiation consisted of electrons oscillating back and forth along magnetic field lines, the flux (being determined by the atmospheric density near the mirror points) should continue to change with altitude well above the 100-km level. It should be further noted that the southern mirror points lie much lower in the atmosphere than the northern ones. For this reason, plus the fact that the flux measured away from the peak in the two June flights and in all directions in the October flight had comparable intensities, we conclude that this radiation as well as that responsible for the main peak consisted (at least for the most part) of soft x rays.

Of course, it is possible that these x rays may be partly of atmospheric origin. Moreover, our arguments do not rule out the possibility that electrons contribute a small, yet appreciable fraction of the radiation. In particular, it is conceivable that electrons may be responsible for the two small peaks observed in the October flight, which are more or less symmetrically located with respect to the magnetic field. On the other hand, if we also ascribe the peaks of the October flight to x rays (and the symmetry requirement of electron fluxes would not permit assigning one of the peaks to electrons and the other to x rays), we find an interesting correlation with results of the two June flights. The large peaks observed in these flights, as already noted, show an asymmetry which could well be due to an unresolved secondary maximum in a general eastern direction. This maximum and the western maximum observed in October 1962 are consistent with a galactic source of x rays located somewhere in the region between 20 and 23 hour R.A. and between +10° and +50° declination (which we shall call source No. 2). The eastern maximum observed in October suggests the existence of still another source (source No. 3) in a general region of the sky near the galactic plane, which incidentally, includes the Crab Nebula. This region was below the horizon in June; therefore, we cannot argue that source No. 3 is outside the solar system on the ground of its having been seen at the same celestial location at different times of the year.

From the absorption coefficients in mica and air measured in the June 1962 experiments, we estimated that the x radiation from source No. 1 had an effective wavelength of about 3 Å. This estimate would appear reasonable for a source located near the galactic center, since interstellar absorption would cut the spectrum sharply above 3 or 4 Å. In this connection, we note that the response of the counter used in June 1962 was limited to a spectral region from about 2 Å to about 10 Å (where the average efficiency was about 15%). The counter used in June 1963 had a similar response, but in the region around 3 Å its efficiency was about four times greater. Thus the fact that the peak counting rate was several times greater in the June 1963 flight than in the June 1962 flight confirms our previous estimate of wavelength. If we make the simplifying assumption that all the x rays received from source No. 1 have a unique wavelength of 3 Å, we can compute their flux φ by means of the equation

$$R = \varphi A \cos\theta \exp(-\mu_w x_w \sec\theta)[1 - \exp(-\mu_g x_g \sec\theta)],$$

where R is the peak counting rate, A is the effective window area, θ is the angle between the normal to the Geiger counter and the source (assumed to be a point) at the time of closest approach, μ_w and μ_g are the absorption coefficients of 3Å x rays in the window and in the filling gas, respectively, and x_w and x_g are the thicknesses of the window and the gas. Under the assumption that source No. 1 is located at 17 hour R.A., -22° declination, and using as a background the minimum counting rate observed during the rotation of the rocket in each instance, we obtain a flux value of 28.0 ± 1.2 cm^{-2} sec^{-1} from the June 1962 flight, and a flux value of 20.5 ± 0.4 cm^{-2} sec^{-1} from the June 1963 flight. The errors quoted are purely statistical; the systematic errors, due mainly to the uncertainty in the effective wavelength, are potentially much larger. Notice that in our previous paper we had underestimated the flux level because we had taken for A the geometric rather than the effective area of the window, and because we had taken for R the average counting rate in the peak region rather than at the peak itself.

It is not possible to evaluate with any degree of accuracy the absolute fluxes from sources No 2 and No. 3 because the location of these sources is not well known, because no reliable estimate of their spectrum is available, and especially because the uncertainty in the background to be subtracted affects the estimated counting rates produced by sources No. 2 and No. 3 much more than it does the counting rate produced by the stronger source No. 1. We only wish to point out that if one considers the different efficiencies of the Geiger counters used, there is no evidence of changes in the fluxes observed in any given celestial direction during the three flights.

In our previous paper, we quoted the view expressed by Clark[3] that the x rays revealed by our observations might result from the synchrotron radiation of 10^{14}-eV cosmic electrons produced by interactions of very high-energy cosmic rays with interstellar matter. We cited preliminary evidence from the Bolivian Air Shower Joint Experiment for the existence of 10^{14}-eV cosmic γ rays,[4] which also would arise from such interactions. This evidence has not been confirmed by later results.[5] Furthermore, Ginzburg and Syrovatskii[6] have shown that, if one accepts current values of the galactic magnetic field, matter density, and cosmic-ray flux, it is not possible to account for the observed x rays via this mechanism. Other possible mechanisms for the production of x rays, either as an isotropic background or from localized sources along the galactic equatorial plane, have been discussed by Felton and Morrison,[7] Hoyle,[8] Hayakawa and Matsuoka,[9] and Gould and Burbidge.[10] On the other hand, Freidlander[11] has taken the view that the density of high-energy electrons in galactic space may be sufficiently greater than the presently estimated value to afford the required source via synchrotron radiation.

One mechanism suggested by Gould and Burbidge places the core of an x-ray source at the radio center of the galaxy. Our experiments reveal a main source close to the center of the galaxy but apparently not quite coincident with it. Obviously, further experiments with instruments affording better angular resolution are of vital importance to settle this problem. Other important questions requiring early attention are the structure of the secondary sources indicated by our experiments, the possible existence of an isotropic x-ray flux (which may be of extragalactic origin), and the spectral distributions of the observed radiation.

We wish to thank Professor M. Oda for many stimulating discussions concerning experimental techniques and possible source mechanisms. We also wish to acknowledge the continued encouragement and technical assistance of Dr. John W. Salisbury, Branch Chief, Lunar and Planetary Research Laboratory, Air Force Cambridge Research Laboratories, and personnel from both Air Force Cambridge Research Laboratories and the White Sands Missile Range, White Sands,

New Mexico.

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*The research reported in this paper was sponsored by the Air Force Cambridge Research Laboratories, Office of Aerospace Research, under Contract AF 19(628)-1605.

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[3] G. Clark (to be published).

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ALTERNATIVE APPROACH TO THE PROBLEM OF PRODUCING CONTROLLED THERMONUCLEAR POWER

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(Received 4 November 1963)

The attempt to achieve controlled thermonuclear power with low-density magnetically confined plasmas is confronted with many difficulties. It is therefore important that we should examine the problem from as many different points of view as possible. In the approach suggested here macroscopic particles are accelerated to 10^8-10^9 cm $\sec^{-1}$; they then collide either with other particles or a target, and their kinetic energy is converted into thermal energy inertially confined to a small region for a short period of time. Only a crude analysis is offered, and the problem of accelerating macroscopic particles to a high energy is ignored.

Provisionally we assume that (i) the energy radiated from the impact region is small compared with the initial kinetic energy, and (ii) all reaction products escape from the impact region. For simplicity it is supposed that the particle is a right cylinder, of diameter D and length L, with its base facing the target.

First, we consider $L = D$ (an approximation for a spherical particle). We assume that a one-dimensional fluid treatment is adequate during the time taken for a shock wave to travel through the particle. Because of (i) and (ii), the temperature T is almost constant during impact and we use the steady-state equations of continuity, motion, and energy. Let a particle have a velocity v and density ρ, and a stationary target have the same density; then behind the shock fronts advancing into the particle and target, the density and pressure are

$$\rho_1 = 4\rho, \quad p_1 = \tfrac{1}{3}\rho v^2 \tag{1a,b}$$

for $\gamma = \frac{5}{3}$, and neglecting ionization energy. If z is the distance separating the shock fronts, $dz/dt = \frac{1}{3}v$, and $z = \frac{1}{2}D$ at the end of the impact period $t_1 = 3D/2v$.

Optimistically we suppose that the particle and target consist solely of hydrogen isotopes; then $p_1 = 2n_1kT$, $\rho_1 = n_1 m_{\mathrm{H}} A$, where n is the ion density and A the mean atomic weight. The power radiated by free-free transitions is[1]

$$P_b = 5.2\times10^{22}\rho_1{}^2 A^{-2} T^{1/2} \text{ erg cm}^{-3}\text{ sec}^{-1}, \tag{2}$$

and (i) is therefore true if

$$\int_0^{t_1} P_b z\,dt / \tfrac{1}{2}\rho D v^2 \ll 1.$$

Using (1a), (1b), and (2), it follows that

$$\rho D \ll 1.4\times10^{-8} A^{1/2} T \text{ g cm}^{-2}. \tag{3}$$

The reaction power per unit volume is

$$P_r = \alpha \rho_1{}^2 A^{-2} \langle \sigma v \rangle,$$

and the ratio R of energy released to the energy