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Balloon X-Ray Astronomy

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I. Introduction

THE most exciting recent result of space research has been the discovery of strong x-ray emitting astronomical objects. In the four years since the first indications, researchers at Massachusetts Institute of Technology, American Science and Engineering,[1] the Naval Research Laboratory,[2] and Lockheed[3] have located about twenty discrete sources. Some of these have been positively associated with known radio or optical objects; most are presently unidentified. Some may be of extra-galactic origin.[4] The intrepretation of these sources in terms of the physical processes involved requires position, angular size, intensity, and spectral measurements. Although the initial discovery and investigation of x-ray sources has been accomplished from rockets, much early exploratory work searching for extra-terrestrial x rays and γ rays has been carried out from balloons. Since the first positive results were obtained in 1964, balloon observations have paralleled the rocket work in developing the field of x-ray astronomy. Satellite work, thus far, has been of an exploratory nature, and because of the long lead time, a definitive x-ray experiment has only recently been launched into orbit. In this paper we shall discuss briefly some of the instrumental and observational aspects of balloon x-ray astronomy, and its contribution toward understanding the physics of these sources.

II. Theoretical Considerations

Theoretical astrophysicists in the late fifties predicted detectable γ-ray fluxes from celestial objects,[5] thus providing impetus for the early exploratory work. These predictions were based on the evidence for energetic processes on a cosmic scale accumulated through optical, radio, and cosmic-ray observations. Gamma rays from the mechanisms then considered have not generally been observed; in particular, the prediction of line emission due to nuclear interactions in cosmic space, or near stellar surfaces, has thus far failed to materialize. Other processes, such as synchrotron emission and radiation from very hot gases, seem most important today.[6] These emission mechanisms produce their most intense fluxes in the x-ray spectral range. The interplay between observation and theory is particularly close in a developing field such as modern high-energy astrophysics.

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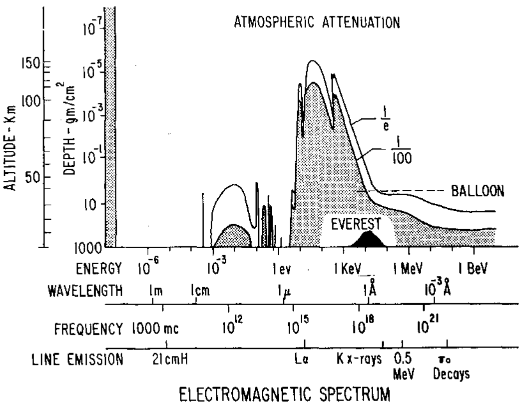


Fig. 1 Absorption of the astronomical electromagnetic spectrum by the earth's atmosphere. The altitude and depth at which radiation is attenuated to $1/e$ and $1/100$ of its initial value are shown as a function of the energy, frequency, and wavelength of the incident quanta. Optical and radio "windows" are obvious. X-ray observation above 20 kev may be made from balloons.

The relation of x-ray observations to more conventional astronomy is indicated in Fig. 1, which shows a wide range of the electromagnetic spectrum. The abscissa shows relations between wavelength, frequency, and energy and the wavelengths at which important line emissions have been observed or predicted. The shaded areas show the absorption of extra-terrestrial radiation by the overlying earth's atmosphere. The "optical" and "radio" windows, through which all ground-based astronomy is done, are apparent. The structured region in the infrared also allows cosmic observations; new and interesting discoveries are now being made here.

At wavelengths shorter than about L_α, all observations must be made above the atmosphere. Observations in the range of about 10 to 1 Å, corresponding to photon energies of 1 to 10 kev, must be carried out at altitudes of several hundred kilometers; this, therefore, is roughly the range of rocket x-ray astronomy. At energies above about 20 kev, photons will easily penetrate below 40 km, into the range of balloons. In this paper we shall not concern ourselves with the important work being done from balloons and satellites at photon energies greater than 1 Mev: the γ-ray region.

III. Balloon Technique

Modern polyethylene balloons, having volumes of 3 to 10 million ft^3, will inexpensively maintain several hundred pounds of apparatus at altitudes of 130,000 to 140,000 ft for many hours. Here, only a few tenths of a percent of overlying atmosphere remain. The advantage of long observing time, in contrast to the few minutes obtainable during a rocket flight, is partly offset by the weaker fluxes encountered at the higher energies. Furthermore, the background γ-ray problem is considerably more severe.

The background problem has indeed been the central problem of x-ray and γ-ray observations. The x-ray fluxes from strong sources are about 10^{-2} photons/cm^2-sec at an energy of 30 kev. Any additional fluxes higher than this value are an appreciable background. At balloon altitudes, or in space, one is exposed to the full flux of galactic cosmic rays. These highly interacting particles have an average energy of 3 bev and an intensity of about 1/cm^2-sec. Processes that convert these 3-bev particles into 30-kev photons in the atmosphere or in the apparatus thus need be efficient only to 10^{-7} to produce fluxes equal to the cosmic x-ray fluxes. Figure 2 shows the cosmic-ray produced atmospheric γ-ray spectrum, as measured with various detectors at 130,000 ft over Texas.[7–10] Strong x-ray sources are about $\frac{1}{10}$ as intense; therefore, efficient methods of collimation or background correction must be used.

Because of the short wavelength of the photons studied by balloon workers, imaging and focusing techniques cannot be used; therefore, "telescopes" in the usual sense cannot be constructed. The detectors are similar to nuclear detectors, usually being combinations of scintillation counters. Even the longer wavelength photons available to rocket observers are usually detected with thin window Geiger or proportional counters, although Giacconi has pioneered the use of grazing incidence optics useable in the 1–10 Å range.[11]

Various investigators have used different observational techniques. The initial cosmic x-ray discovery from balloons, an observation of Crab Nebula x rays by George Clark[12] of M.I.T., was made using a simple idea. A large area, thin scintillation detector with a passive lead collimator was rotated slowly against the balloon. The detector thus scanned the sky across the object under study, in a manner usually employed by rocket observers. By superimposing many such scans, a statistically significant increase in the counting rate was found in the direction of the Crab Nebula. Large arrays of such detectors, having total areas of many hundreds of square centimeters, have been used recently by groups at M.I.T. and at the Graduate Research Center of the Southwest.[13]

Another technique, originally suggested for γ-ray astronomy by Kenneth Frost of the Goddard Space Flight Center,[14] is to make the collimator out of a scintillating material and connect this in electrical anticoincidence with the detector proper. Such devices have rather excellent background properties since x rays produced by cosmic rays in the shield are vetoed out. These detectors, however, tend to be rather massive and expensive and are limited in area. Systems based on this idea have been used by Haymes at Rice University,[15] and have been extensively developed here at the University of California at San Diego (U.C.S.D.). Schemes using various combinations of active and passive shielding have also been used successfully, notably by Boldt

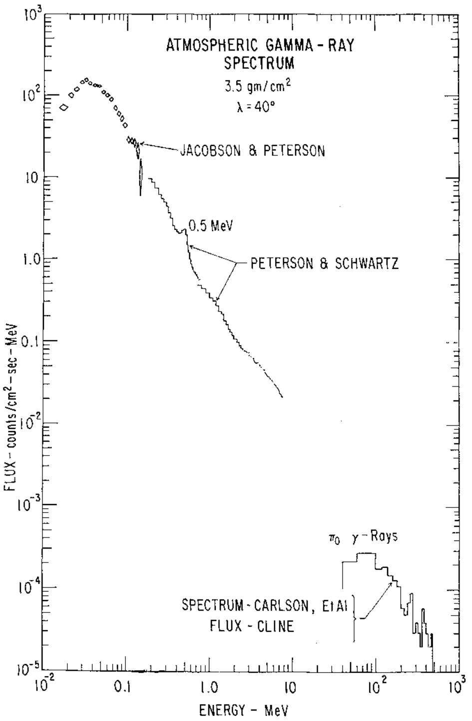
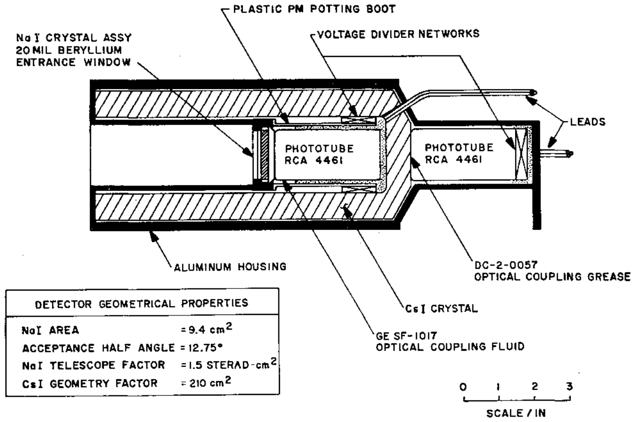


Fig. 2 The spectrum of atmospheric γ rays measured at 130,000 ft over Texas, where many balloon studies are conducted. Observation of cosmic sources through this large cosmic-ray-produced background requires efficient collimation and anticoincidence techniques.



DETECTOR GEOMETRICAL PROPERTIES	
NaI AREA	= 9.4 cm^2
ACCEPTANCE HALF ANGLE	= 12.75°
NaI TELESCOPE FACTOR	= 1.5 STERAD-cm^2
CsI GEOMETRY FACTOR	= 210 cm^2

Fig. 3 A detector used to measure cosmic x rays over the 10- to 200-kev range. The CsI "active" collimating shield, in electrical anticoincidence with the thin NaI central detector, attenuates low-energy photons and rejects production due to energetic cosmic-ray processes.

of the Goddard Space Flight Center,[16] and by Overbeck at M.I.T.

IV. Balloon Instrumentation

The detector used at U.C.S.D. is shown in Fig. 3. This was originally developed as a satellite instrument for an Orbiting Solar Observatory that was launched in early 1967.[17] The prototype version has been used on balloons to obtain many of the results in this paper. The detector consists of a thin NaI scintillation counter surrounded by a collimating anticoincidence shield of CsI, 2 cm thick. The detector has an area of 10 cm^2 and an angular aperture about 25° wide total. The resolution obtained for monochromatic γ rays is that typically obtained by scintillation counters at these energies, about 30% at 80 kev. Background rejection is such that at 130,000 ft, about 80% of the events over the 10- to 200-kev range are atmospheric or cosmic x rays entering the forward aperture. The total good event rate is about 2 counts/sec. The apparatus used for cosmic x-ray observations is shown in Fig. 4 and in the block diagram (Fig. 5).

Events from the detector are converted in the 128-channel pulse-height analyzer to a digital code group that is transmitted, along with synchronization and identification information, as a word on a PCM/FM/FM telemetry system. Auxiliary information relative to total counting rates, detector mode, servo-performance, and housekeeping data are modulated onto other FM subcarriers. Telemetry range from a balloon at 130,000 ft is about 400 miles. The use of standard telemetry practices allows commercially available equipment to be used in a simple ground setup (Fig. 6). Events after decommutation are accumulated in the memory core of a standard pulse-height analyzer, which is read out in a punched tape format for computer analysis.

As shown in Fig. 4, the detector is mounted in a gimballed frame. The detector head is pointed in azimuth, using the earth's magnetic field as a reference, and the gondola itself as a reaction inertia. Elevation positions are programmed with a timer, as is the calibration γ-ray source. About once an hour, this source, mounted on the end of a motor-driven vane, moves over the detector aperture for about 5 min. This source is visible in the photograph, as are the reference and readout azimuth magnetometers, various components of the telemetry and servo system, and the lead-acid battery supply. The main azimuth shaft, motor, and slip rings are enclosed in the central column. During flight, the entire apparatus is placed in a thermalizing Styrofoam box, which is suspended through the parachute to the balloon.

In the usual observing mode, the detector is pointed approximately north or south at a fixed elevation. A cosmic x-ray source thus makes a meridian transit through the detector aperture as the earth rotates. Background data are obtained before and after the transit. In another mode, the aximuth reference magnetometer has been driven with a 24-hr clock. A low-elevation source is tracked approximately, across the sky, thus increasing the observing time. The sun has been tracked directly, using optical sensors.

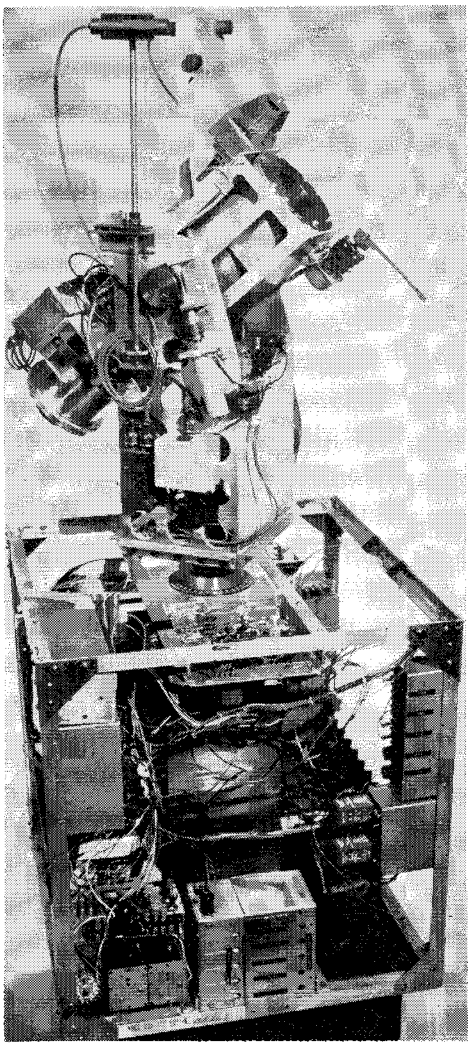


Fig. 4 Balloon apparatus that has been used for many observations at U.C.S.D. The detector of Fig. 3 is gimballed in the alt-azimuth mount and servoed using magnetometers, programmed elevation control, or solar sensors. The bottom portion of the gondola, containing batteries and telemetry, gives a reaction inertia for the servo. The entire gondola, about 1 m high, is packed in a thermally insulated Styrofoam box during flight.

V. Cosmic Diffuse Component

One of the major surprises of x-ray astronomy has been the discovery of a general, or diffuse component, which is apparently quite isotropic over the celestial sphere. This was first indicated from observations in interplanetary space by Ranger III,[18] and subsequently verified by rocket results. These x rays are also detected from balloons, as shown in Fig. 7.[7] Here, the counting rates at low energies, as a function of atmospheric depth, increase as the balloon rises, indicating the presence of an external x-ray flux that is no longer being absorbed by the atmosphere. Because of the difference in spectral shape of the atmospheric background and the diffuse cosmic flux, atmospheric γ rays are dominant at higher energies. Here the depth dependence is more typical of locally produced background.

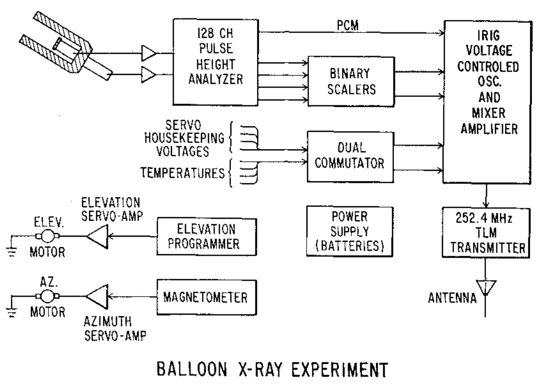


Fig. 5. Simplified block diagram of the apparatus in Fig. 4. Pulse spectral data is coded with a 128-channel nuclear-type pulse-height analyzer, and transmitted, along with performance monitoring information, on a standard PCM/FM/FM telemetry link.

The combination of rocket, balloon,[19] and satellite[20] observations form the spectrum shown in Fig. 8. The diffuse component apparently extends continuously from the few kev to several, perhaps even a hundred, Mev. Because of their isotropic nature, these x rays must have their origin beyond our galaxy, from some interaction in the universe as a whole. It has been postulated that these x rays are produced by cosmic-ray electrons scattering on photons in intergalactic space.[21] This idea has been given considerable credibility following radio astronomers' recent discovery: the universe as a whole also radiates like a blackbody at 3.5°K and thus provides an ample density of low-energy photons.

VI. Point Sources

Most of the point sources initially discovered were found to lie in the direction of the galactic center. They were therefore assumed to be of galactic origin.[2] Attempts to identify the sources with supernovae remnants, the remains of very energetic stellar explosions, have generally failed, with a few notable exceptions. At present, only two well studied sources, the Crab Nebula and Scorpius XR-1, are definitely associated with objects known from radio and optical astronomy, although other identifications seem likely. X-ray emission has now been tentatively identified with two strong extra-galactic radio sources, Cygnus A and Virgo A.[4] For recent work on the identification of objects in the Cygnus Region, see Ref. 29.

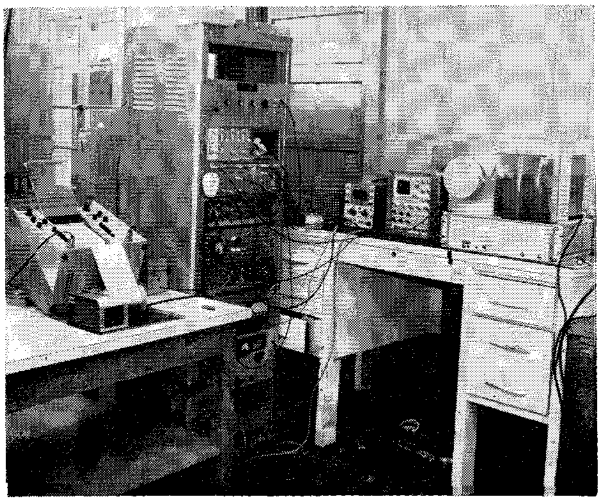


Fig. 6 The simple ground setup that permits recording of the balloon telemetry signals from line of sight, about 400 miles. The station also provides for real time quick-look data decommutation and display.

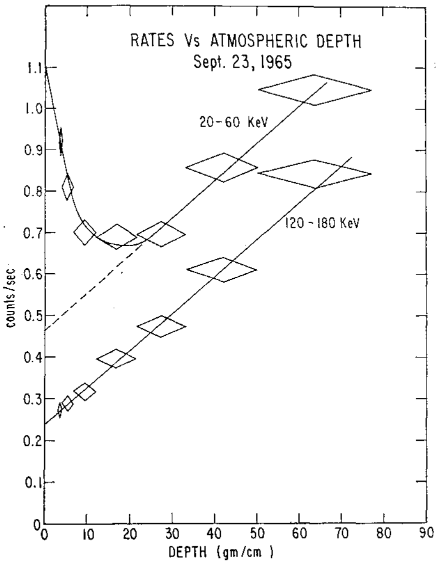


Fig. 7 Counting rates over two energy ranges observed, with the detector pointing vertically upward, as a balloon rises to its final altitude. The increase in rates at low energies is apparently due to an isotropic background of cosmic x rays from space.

Rocket observations have generally provided positional and angular size data; detailed spectral information to the highest energies has been obtained from balloon work. The Crab Nebula and Scorpius XR-1, the identified sources, also have the most precise spectral data available. The spectrum from most of the other sources is completely unknown; a few have been classed as "hard" or "soft." Recently, with the discovery of an extended source near the galactic pole,[16] a new dimension has been added to balloon x-ray astronomy, not previously seen by the rocket observers. The emission has been suggested to be extra-galactic, identified with the Coma cluster of galaxies. The possibility of detecting and locating objects considerably enlarges the contribution balloon observations can provide to x-ray astronomy.

As previously indicated, the Crab Nebula, one of the sources discovered by early rocket observations, was the first x-ray

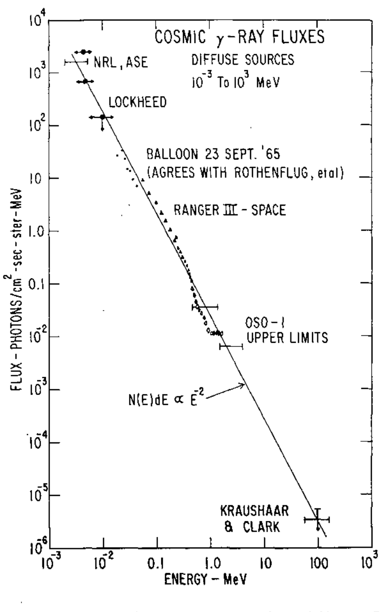


Fig. 8 The spectrum of the isotropic diffuse background, as obtained from many rocket, balloon, and satellite observations. These x and γ rays may originate from interactions in intergalactic space.

emitter found from balloons. This remarkable and well-studied object, one of the strongest radio sources in the sky, is the result of a supernova explosion that was seen in the year 1054. In the 900 years since the event, the object has expanded to form a luminous gas cloud about 5 light yr across. In a remarkable rocket experiment, Friedman and his collaborators at the Naval Research Laboratory used a lunar occultation and showed that the x-ray emission occurred over a region centered on the optical nebula, but only 1 or 2 light yr across.[22]

Our observation of Crab Nebula x rays was made September 23, 1965. Counting rates of the detector are shown as a function of time in Fig. 9, which also indicates many features of a balloon x-ray observation. During ascent, background atmospheric γ rays are counted. The maximum in the rate at about 70,000 ft is associated with the maximum in cosmic-ray intensity at this altitude. The increase in flux as the balloon approaches its limiting altitude some 2 hr after launch is caused by the extra-terrestrial diffuse x rays discussed previously. After reaching altitude, the servo was turned on and background data were collected until the Crab Nebula made its transit through the detector. This resulted in the enhanced rates shown. The actual source spectrum is obtained by correcting the difference in counting rate at various energies for area, channel width, efficiency, and atmospheric absorption. The various results for Crab Nebula x rays are shown in Fig. 10. Our observations indicate the spectrum[23] is of a power law form, which may be indicative of a synchrotron origin for the x rays. These results seem in direct conflict with the work of Haymes,[15] who has observed an exponential spectrum. The differences may be resolvable in terms of instrumental corrections, or variations with time of the source itself. Clearly, more x-ray observations of the Crab Nebula are needed.

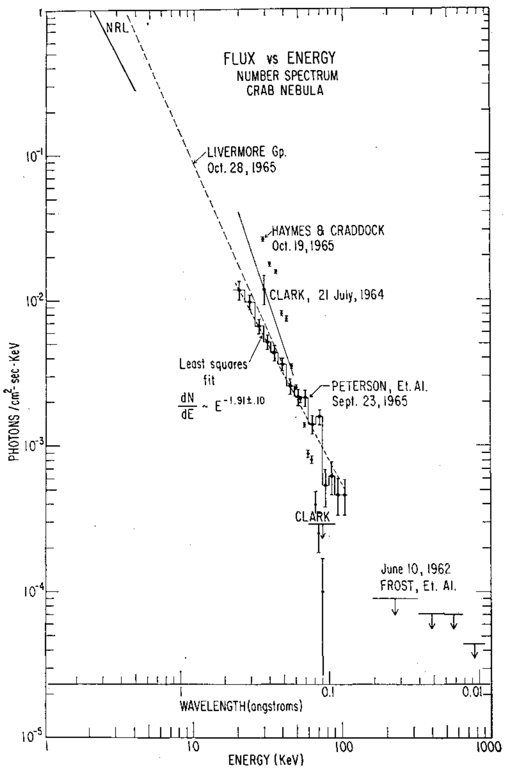


Fig. 10 Various rocket and balloon determinations of the Crab Nebula x-ray spectrum. A power law spectrum may be indicative of a synchroton emission process.

Another source of a very different character is Scorpius XR-1, the strongest x-ray emitter in the sky. This object has been intensely studied by Giacconi's group at ASE-M.I.T. They have succeeded in measuring its angular size to be less than 20 arc-sec,[24] and set the stage for an optical identification with an old nova.[25,26] Because of its location and intensity, this object is thought to be close, probably within a few hundred light years. The spectrum obtained from rocket and balloon work is shown in Fig. 11.[27] The shape is exponential over a wide range, characteristic of a hot gas at about 50 × 10^6

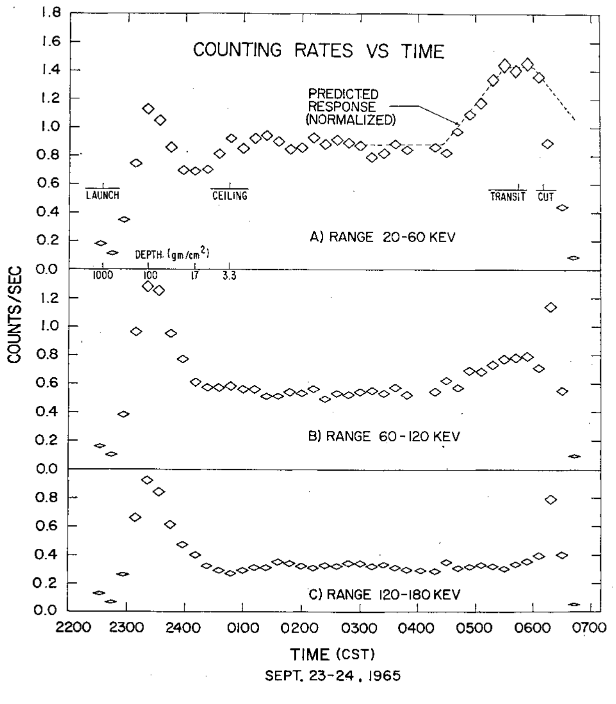


Fig. 9 Counting rates measured during an observation of the Crab Nebula in 1965. The detector of Fig. 4 was held at a fixed elevation and pointed south in aximuth, while the source made a meridian transit through the instrument aperture.

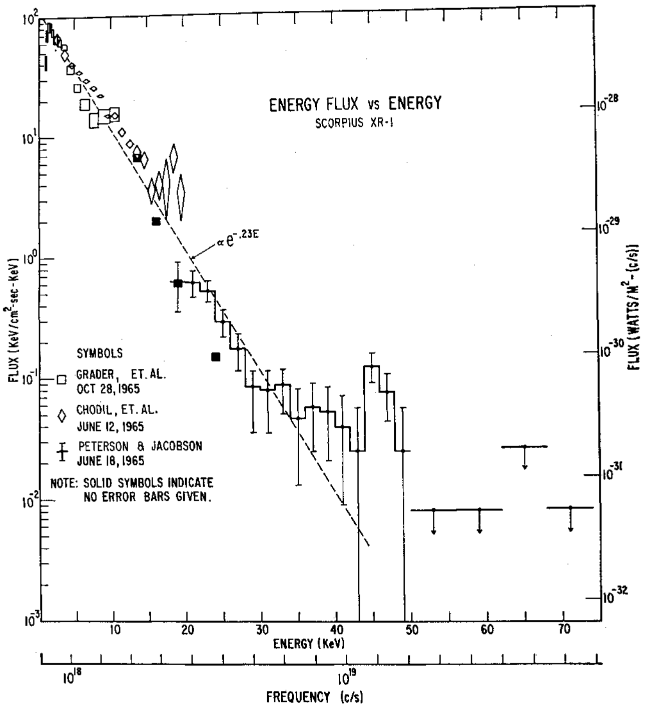


Fig. 11 The spectrum of Scorpius XR-1, the most intense x-ray source at energy ranges accessible to rocket-borne instruments. The exponential spectrum is indicative of thermal bremsstrahlung from a hot ionized gas at 50-million-deg temperature.

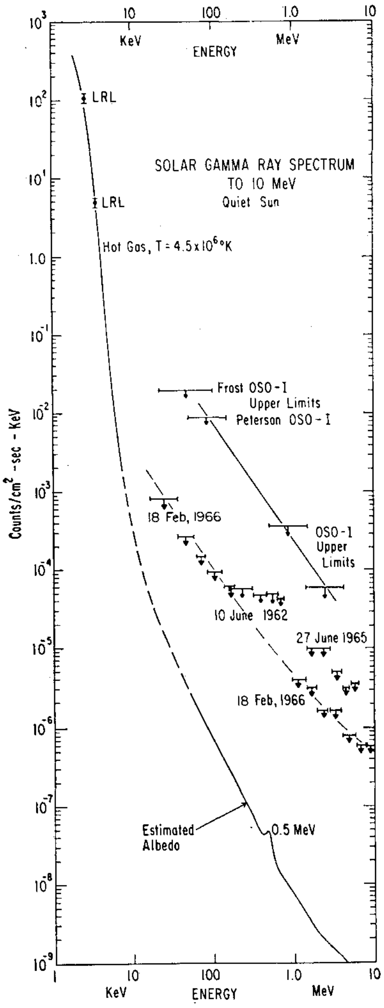


Fig. 12 Only upper limits on x- and γ-ray fluxes are available for the quiet sun at energies above 20 kev. Rockets, however, have provided considerable data on coronal x-ray emissions. Solar flares have occasionally produced transient events of considerable intensity in the 20- to 100-kev range.

°K. At higher energies, there apparently is an additional component of emission.

Astrophysicists have not yet produced a theory that explains the properties of Scorpius XR-1. If, indeed, the object is a thermal emitting gas, how was it heated initially? How does it maintain its temperature? Why does it remain contained in a very small volume? Are the other x-ray objects similar to Scorpius XR-1, to the Crab, or to neither? Answers to these and other questions will be provided by further observations and theoretical developments as the story of x-ray astronomy unfolds.

VII. The Sun

Most of the sources previously discussed are of a rather unusual nature, having most of their luminosity in the x-ray region. The sun, however, is a very close star of a standard variety. As shown in Fig. 12, only upper limits to the quiet sun are available in the balloon energy range,[28] although transient x-ray bursts have been observed accompanied by solar flares. The sun is very well characterized as a blackbody radiating at 6000°K, surrounded by a hot gas, the solar corona, at several million °K. This radiation, shown in the figure, has been studied intensively from rocket and satellite observations. Searching for higher energy solar x- and γ-ray emissions will continue for some time.

VIII. Future Developments

New instruments are presently under development at U.C.S.D. which will provide larger areas, smaller solid angles, better energy resolution, and lower background—all requisites to the extension of our knowledge about cosmic discrete and diffuse x- and γ-ray sources. The components of one such instrument are shown in Fig. 13. Interchangeable NaI(Tl) detector assemblies, two of which are shown at the right and left edges of the figure, are placed inside the large NaI(Tl) "well" crystal, which forms a portion of the anticoincidence, or "active" shield. The collimator is made of a CsI(Na) scintillation crystal drilled to form a honeycomb. This is viewed by photomultiplier tubes, and placed in electrical anticoincidence with the detector, completing the "active" shield. The resulting instrument has much larger area than the orbiting solar observatory (OSO) detector described previously, much lower background fluxes, and an aperture of only a few degrees. The weight of the over-all instrument is only 60 lb. Balloon test flights of this system have been completed and show that the detector background is a tenth that of previous instruments of this nature. A similar version of this instrument is scheduled for launch aboard an OSO satellite in 1970.

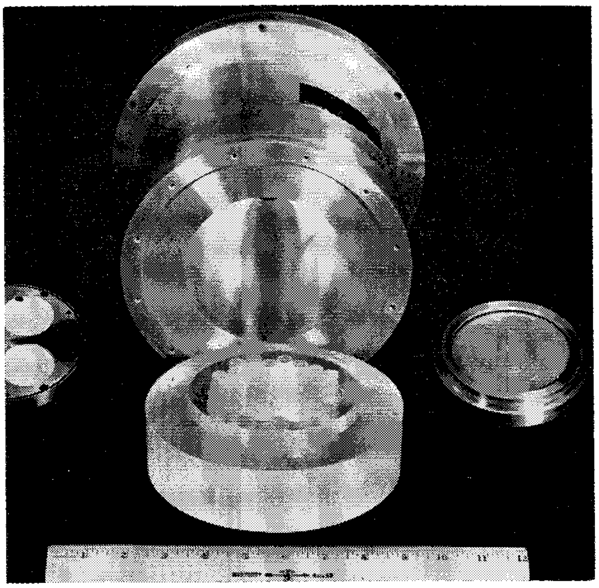


Fig. 13 Scintillation components of a large area, highly collimated detector developed at U.C.S.D. for balloon work. A similar version is planned for an OSO satellite in 1970.

Also under development at U.C.S.D. is a collimated detector system incorporating lithium-ion drifted germanium detectors whose energy resolution is far superior to that of NaI, allowing finer details of spectral structure to be observed. These and other new instruments being created in several laboratories will soon provide many more measurements of cosmic x- and γ-ray sources, at intensity levels undreamed of only a few years ago.

Future balloon-borne detector systems will consist of arrays of scintillation or solid-state counters with very large areas and massive anticoincidence collimating shields. Such instruments will require much more elaborate pointing controls than have been used in the past, probably involving star trackers. Elaborate command and data-handling systems are now being planned. The developments will have to be matched by developments in balloon technology as the heavier apparatus will require larger balloons.

IX. Summary

In this paper, we have attempted to summarize some of the contributions of balloon-borne experiments to the field of x- and γ-ray astronomy, and relate them to other observations and theoretical ideas of high-energy astrophysics. Although in the distant future long-term observations and γ-ray astronomy will undoubtedly be done from orbiting vehicles, balloon work will long provide an economical and timely means of carrying out exploratory studies and testing instrumental ideas for satellite application. It is now, when rockets are limited by flight duration and the time between inception and launch of satellite instruments is so long, that balloon-borne experiments are most important for observing the higher energy x and γ rays with the very latest instrumentation and techniques.

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