BALLOON-BORNE HARD X-RAY STUDY OF THE SOUTHERN SKY

DUNSTAN DUEN-SHINN GUO

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OF THE SOUTHERN SKY

DUNSTAN DUEN-SHINN GUO

B.A., National Taiwan University, China, 1966
M.S., University of New Hampshire, 1969

A THESIS

Submitted to the University of New Hampshire
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To the memory of my mother
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ABSTRACT

BALLOON BORNE HARD X-RAY STUDY OF THE SOUTHERN SKY

by

DUNSTAN GUO

A NaI(Tl) scintillation telescope-spectrometer with a sensitive area of 450 cm$^2$ and an aperture of 6° x 14° FWHM was designed and built for high-altitude astronomical observation in the photon energy range of 17 keV to 1.5 MeV. During an 8-hour balloon flight in Argentina on November 22, 1971, the instrument was utilized to survey the galactic plane and its vicinity between $\ell^{\text{II}} = 285^\circ$ and $\ell^{\text{II}} = 25^\circ$, including the galactic center. In the hard x-ray profile of the galactic plane obtained, a total of eleven sources were observed. They could be identified with sources CEN X-5, GX 301-2, GX 304-1, CIR X-1, NOR X-2, GX 340+0, NOR X-1, GX 349+2, GX 357+2.5, and the group of sources near the galactic center. CEN X-5 and GX 357+2.5 were observed in the hard x-rays for the first time. GX 331-1 was possibly a new source. Spectra of these sources were measured between 17 keV and 500 keV, and their corresponding spectral characteristics were derived. The intensities are generally in good agreement with previous hard x-ray observations below 100 keV except for certain highly variable sources. However, a comparison with available soft x-ray data from rocket and satellite experiments shows some inconsistencies probably due to either
temporal variability or the existence of separate hard x-ray components in the emission. The complex hard x-ray spectra of three sources -- NOR X-2, GX 331-1, and GX 340+0, suggest that they might be similar to SCO X-1. The spectral hardness below 100 keV differs considerably in the hard x-ray spectra of the observed sources, but there seems to be no correlation of this spectral hardness with the x-ray luminosity classification of Seward et al. (1972).

A search for extraterrestrial gamma ray line emission near 0.5 MeV has set an upper limit of $1.7 \times 10^{-3}$ photons/cm$^2$ sec for most of the celestial area covered by the observation, including the galactic disk, and of $(3.2 \pm 1.5) \times 10^{-3}$ photons/cm$^2$ sec for the galactic center region.
CHAPTER I

INTRODUCTION I: X-RAY ASTRONOMY

1.1 BRIEF HISTORY OF X-RAY ASTRONOMY

Electromagnetic radiation has long been the dominant medium through which man observes and seeks understanding of the Universe he lives in. But the overlying atmosphere is transparent to only two portions of the long stretch of energies: namely, the visible region and the radio region (Fig. 1.1, p. 2), plus some narrow bands in the infrared. Although ground-based observations have over the years collected an enormous amount of information through their "windows", the emerged picture of the universe is not a complete one. From stellar evolution to cosmology, there are many questions that cannot be answered by optical and radio observations alone.

During the last two decades, with the advent of new radiation detection techniques as well as high-flying vehicles such as balloons, rockets, satellites, and space probes, it is only natural to see attempts and discoveries which allowed observations above the obscuring atmosphere and established "new astronomies" in the formerly inaccessible regions of the electromagnetic spectrum: first ultraviolet, then x-rays and
Fig. 1.1 Transmission of electromagnetic radiation from radio wave to GeV gamma rays in the atmosphere. Shown in fractional transmission as functions of wavelength and altitude.
gamma rays, with the photon energy involved ever increasing.*

Since 1948, the sun has been known to be emitting x-rays, especially during solar flares. But the average intensity of emission from the sun is so small that there was not much serious expectation of observing x-rays from other celestial objects outside the solar system. Then in 1962, a rocket-borne x-ray detector, sensitive to 1.5 keV to 6 keV photons, was flown to investigate possible scattering of solar x-rays by the lunar surface, but instead x-ray emission of non-solar origin was discovered — amidst a seemingly diffuse background flux, there was a very strong localized source (or sources) in the direction of the constellation of Scorpio [Giacconi et al. (1962)] — thus marked the beginning of an exciting branch of astronomical research as well as the opening up of a whole new realm of astrophysical phenomena.

Shortly thereafter, more sensitive and well collimated rocket experiments not only confirmed the existence of a strong discrete x-ray source in Scorpio (designated SCO X-1) and the diffuse x-ray background, but also detected x-rays from a

*For the purpose of this thesis, the author will adopt the following nomenclature for the different regions in the "high-energy" portion of the electromagnetic spectrum:

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<td>0.1 keV to 10 keV</td>
<td>Soft x-rays</td>
</tr>
<tr>
<td>10 keV to 200 keV</td>
<td>Hard x-rays</td>
</tr>
<tr>
<td>200 keV to 10 MeV</td>
<td>Soft γ-rays</td>
</tr>
<tr>
<td>10 MeV to 1 GeV</td>
<td>Hard γ-rays</td>
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The sometimes inconsistent nomenclature currently appearing in the literature will be "normalized" according to the above.
source in Taurus (designated TAU X-1) [Gursky et al. (1963); Bowyer et al. (1964a)]. The Taurus source was soon identified as the Crab Nebula, a supernova remnant well observed in both optical and radio frequencies. The new breed of "X-ray astronomers" grasped an unusual opportunity in 1964 -- the lunar occultation of the Crab Nebula -- to measure the exact position and size of TAU X-1. The observed slow eclipse of the x-ray source showed that the emission comes from an extended region, with similar dimensions to that of the optical nebula [Bowyer et al. (1964b)].

Using a wire-grid modulation collimator, the discoverers of SCO X-1 gradually narrowed down its size to be less than 20". And the simultaneous accurate position determination has led to its optical identification -- a flickering ultraviolet star [Sandage et al. (1966)] of visual magnitude between 12 and 13. As a result, astronomers could in fact determine its distance from the earth [Wallerstein (1967); Westphal et al. (1968)]* hence its energy output.

At the same time, more and more discrete x-ray sources were observed and measurements were extended to higher and higher energies. Balloon-borne counter-telescopes detected hard x-rays from several sources, including the original SCO X-1 and TAU X-1 [Clark (1965); Peterson and Jacobson (1966)]. A lunar probe measured a steady diffuse cosmic background flux

*For an optical stellar object, distance determination is usually based on i) color excess (B-V) in the optical spectrum, ii) strength of absorption lines appearing in a continuum spectrum.
up to more than 2 MeV, well into the γ-ray energies [Metzger et al. (1964)].

In 1967, soft x-rays from two extragalactic sources were detected: The radio galaxy M87 in the Virgo cluster and the brightest quasar, 3C273 [Friedman (1967)]. And perhaps more surprising for the astronomer, a "nova"-like x-ray source was suddenly born in Centaurus, rising in intensity to match that of SCO X-1 and gradually declining to below detectability in several months. Yet no optical counterpart was observed [Bowyer et al. (1968)].

Stellar objects pulsating in radio emission (the pulsars) were first observed in 1968 [Hewish et al. (1968)]. The discovery of the fastest pulsar NP0532 (period = 0.033 seconds) in the center of the Crab Nebula prompted the x-ray astronomers to look at the temporal behavior of TAU X-1, and indeed there is 10 to 15% of x-ray flux pulsating in the same manner, hence coming from NP0532. Together with information from γ-ray measurements, a more complete and consistent picture of the system known as the Crab Nebula began to emerge. Now it is generally believed that there is a rapidly rotating neutron star embeded in an expanding cloud of gas, both the product of a well-recorded supernova outburst that occurred in 1054 A.D. The neutron star is the energy source which powers emissions at all energies [Apparao (1973)].

Meanwhile, in addition to radio emission at centimeter wavelengths [Ables (1969)], SCO X-1 was observed to have sudden "flare-like" activities in x-rays [Lewin et al. (1968)].
Hard x-ray measurements showed that the emission spectrum departs from a thermal one at higher energies [Peterson & Jacobson (1966); Lewin et al. (1968)]. Simple-minded emission models for the x-ray "star" had to give way to more complicated or innovative ones [e.g. Cameron and Mock (1967)].

In 1971, the first scientific satellite devoted exclusively for x-ray observation was successfully put into operation. It carried a bank of collimated proportional counters sensitive to x-rays of energy 2 to 20 keV, and capable of locating x-ray sources down to 1' in angular diameter. The observatory has not only provided a surprising catalog of more than 160 x-ray sources (about 35 of which were known previously), galactic and extragalactic (Fig. 1.2, p. 7 ) [Giacconi et al. (1972); Giacconi et al. (1973)], but has also discovered new and highly significant features of individual sources.

First of all, short-time fluctuation in intensity of the x-ray sources was found to be not an unusual phenomenon. In fact, precise periodic variations have led to the discovery of several x-ray eclipsing binaries [Tananbaum (1973)]. On the other hand, highly irregular fluctuations in one case, that of the brightest hard x-ray source CYG X-1, gave astrophysicists strong evidence towards the existence of the theoretical ultimate product of gravitational collapse -- the "legendary" black hole as part of a binary system [Giacconi (1973)].

Having a life span of a little more than a decade,
Fig. 1.2 Distribution of x-ray sources in the 2-6 keV energy range based on the third UHURU catalog [Giacconi et al. (1973)] and results of rocket surveys by Seward et al. (1972). Special source types and source strength (in six grades) are indicated. Some representative sources are labeled. Adapted from Seward (1973).
x-ray astronomy could be called a young science, and yet the wealth of unexpected observational results it has so far produced and the excitement it has caused are perhaps unprecedented. Certainly it has provided enough challenges to both theoreticians and experimentalists. Various theories that have been proposed have had to be continuously modified or, for some, discarded soon enough in order to interpret the rapidly accumulating data. Better instrumentation and techniques for measurement are repeatedly called for to iron out uncertainties or conflicts in the data or to resolve difficulties in interpretation. The development has pulled together the talents of astronomers and physicists in many different fields as well as countries, and it is their combined effort that has put x-ray astronomy ahead as one of the most exciting frontiers of modern science.

1.2 PRESENT OBSERVATIONAL KNOWLEDGE

From a phenomenological point of view, we could divide the observational knowledge as well as theories in x-ray astronomy into four different areas to discuss: The galactic sources, the galactic center, the extragalactic sources, and the diffuse cosmic background.

1.2.1 THE GALACTIC SOURCES

Figure 1.2, (p.7) shows the distribution of 166 known discrete x-ray sources (from the third UHURU catalog [Giacconi et al. (1973)]) in galactic coordinates. About 60 percent (i.e., about 100) of them lie within 20 degrees of the galactic plane and have not been identified with any
known extragalactic objects, and are therefore with one or two exceptions, considered to be sources located within the galaxy [Tananbaum (1973)]. Their number-intensity distribution* shows that there is a spread in intrinsic x-ray luminosity and that only the brighter sources were observed, which seems to be the inevitable result of using detectors of limited sensitivity, together with the presence of a diffuse background.

About 20 of these sources have been identified, with different degrees of certainty, with optical, radio, or infrared objects, and in several cases simultaneously at all these wavelengths. Hence their distances and intrinsic luminosities have been readily determined. For the not yet identified sources, the lower-energy cutoffs of their x-ray spectra could be used as an indication of their distances, assuming some density for the interstellar medium that lies between a given source and the earth. The determined or estimated distances range from 0.5 to 13 kiloparsecs, as shown in the distribution of brighter sources in the galactic plane in Fig. 1.3 (p.10). The resulting x-ray luminosities for the sources lie in the range of $10^{35}$ to $10^{39}$ erg sec$^{-1}$ (2 - 10 keV) [Seward et al. (1972); Illovaisky (1971)]. If the calculations are correct, it seems that there is a

---

*The number-intensity distribution is defined as: The distribution of number of sources that exceed a given apparent intensity vs. different apparent intensities.
DISTRIBUTION OF X-RAY SOURCES IN THE GALACTIC PLANE

Fig. 1.3 Galactic locations of x-ray sources shown together with hydrogen spiral arms. Source type is indicated. Adapted from Seward et al. (1972).
clustering of stronger sources toward the galactic center, while the weaker sources associate with the spiral arms. There is evidence that some of the sources are related to elliptically ring-shaped H II regions in the spiral arms, which suggests that $10^7$ years would be an upper limit for the age of these sources [Haupt et al. (1970)].

The galactic sources can themselves be put into different categories:

a) **Supernova Remnants (SNR)**

So far there are seven sources definitely, several more possibly, identified with galactic SNR's which usually appear as nonthermal radio sources and have shell-like extended structures in both radio and optical frequencies, each being an expanding gas cloud produced in a past supernova explosion.

Among the seven, three SNR's are relatively young, having an age of less than $10^3$ years. They are the Crab Nebula, Cas A, and SN 1572 (Tycho's nova). The Crab Nebula, one of the brightest x-ray sources in the sky, is well observed and best understood. The fact that its emission spectrum is very probably nonthermal all the way from radio to the $\gamma$-rays [Apparao (1970)] with various degrees of polarization ($15 \pm 5\%$ in x-rays [Novick et al. (1972)] ) has strongly suggested that synchrotron radiation (a detailed discussion of x-ray production mechanisms is given in Appendix A, p.170) is the sole responsible emission mechanism. The embedded fast pulsar NP0532 (responsible for $\sim 15\%$ of the total
x-ray emission from the SNR) is believed to be a rotating neutron star supplying continuously the needed relativistic electrons. The total x-ray (1-500 keV) luminosity is about $10^{37}$ erg sec$^{-1}$. X-rays from Cas A and SN 1572 might also be caused by synchrotron radiation, but the low intensities do not permit definite determination of spectral characteristics [Gorenstein et al. (1970)]. No pulsating has been observed and polarization data is lacking.

The older SNR sources (more than $10^4$ years in age) are the Cygnus Loop, Vela X, Puppis A and IC 443. Their x-ray emission are characterized by soft spectra -- intense under 2 keV, and extended source regions that coincide with optical and radio structures [Pounds (1973)]. There is a radio and x-ray pulsar, PSR 0833, in Vela X and a central compact x-ray source is recently found in Cygnus Loop [Rappaport et al. (1973)]. Their steep spectra are compatible with their age, which resulted in the cooling down of the expanding gas cloud (to $T \sim 10^6$ °K) and the steepening of the electron spectra that produces the observed synchrotron x-ray spectra.

Some of the extended nearby SNR, such as the Lupus Loop and several probable SNR's like the North Polar Spur and eta Carinae are suspected to be associated with observed discrete or extended x-ray sources [Pounds (1973)].

b) Stellar X-Ray Sources

Although only a dozen or so of these sources are identified with optical or radio stellar objects [Hilter (1973); Braes & Miley (1973)], they are believed to be
compact objects or systems of compact objects not only because of their small apparent sizes, but also due to the fact that over 60% of them show intensity variability—fluctuations with characteristic time as short as fractions of a second (or as long as months). They are among the most luminous objects in our galaxy, with luminosities in the range $10^{36} - 10^{38}$ erg/sec and yet emit most of their radiation in x-rays, typically $10^3$ times their optical output.

Apparently this kind of source is not large in number: the 90 or so observed are believed to account for most of these sources [Giacconi (1973)]. They seem to differ in their emission spectra as well as temporal behaviors, and precise models of emission spectra as well as temporal behaviors, and precise models of emission are not yet known. Nevertheless, they probably represent late and brief phases in stellar evolution [Matynov (1973)]. At least in some cases collapsed objects, i.e. white dwarfs, neutron stars, or black holes might be involved [Salpeter (1973)].

The individually resolved sources in the Magellanic clouds also belong to this category. With varying degrees of observational knowledge on each source, the majority probably fall into two groups:

(i) **SCO X-1-like sources.** The prime example, is, of course, SCO X-1 which has been observed in detail optically [Johnson (1970)] in radio [Ables (1969)], infrared [Neugebauer et al. (1969)] as well as in x-rays up to 200 keV [Agrawal et al. (1969); Haymes et al. (1972)]. It is the brightest x-ray
"star" below 25 keV. Its optical counterpart has a magnitude of 12.5 and is relatively close to the earth (estimated distance: 200-500 parsec). The soft x-ray spectrum is exponential (implying a temperature of $5 \times 10^7$ K), but measurement in hard x-rays show substantial deviation toward a harder spectrum (Fig. 1.4, p.15). Neither x-ray line emission nor polarization in x-rays have been found. The x-ray variability not only involves intensity and spectral shape [Overbeck and Tananbaum (1968); Gorenstein et al. (1968)], but also the lower cutoff of the spectrum below 1 keV [Moore et al. (1973)]. Flare activities have also been observed in the x-ray energy range [Lewin et al. (1968b); Hudson et al. (1970)]. The optical intensity varies by a few percent in minutes and flares by a factor of 2 in hours. In radio, the flux is weak, yet varies by more than a factor of 40. As yet no firm periodicity has been found in any energy range. The linear size of the source was estimated to be $10^4 - 10^5$ km as derived from infrared observation. Simultaneous x-ray/optical/radio photometry of SCO X-1 has not produced correlations that point to simple models.

Other sources that are similar to SCO X-1 are CYG X-2, which has been identified with a G-type star, and several others (e.g., GX 17 + 2) that have no optical identification perhaps because of obscuration by galactic matter since they lie in the galactic plane.

(ii) **X-ray Binaries.** For a total of seven sources there is evidence that each is a member of a binary stellar
Spectra of representative x-ray sources of different types between 1-500 keV. Shaded area indicates the approximate range of observed variations in hard x-rays. The spectrum of the cosmic diffuse background in a solid angle of 0.1 steradian is included for comparison.
system. The periodicities in the x-ray light curves of five of them (CEN X-3, HER X-1, 2U1700-37, et cetera) gave clear indication they are eclipsing binaries, and three (CYG X-1, HER X-1, and 2U0900-40 in the Small Magellanic Cloud) have been identified with optical binaries. Two eclipsing binaries, CEN X-3 and HER X-1 have pulsating x-ray emission with periods of less than five seconds, indicating a model of a highly compact collapsed object in an orbit around and periodically occulted by a larger and normal star. In one case, HER X-1, an optical counterpart with exactly the same occultation periods was found [Davidsen et al. (1972)]. Yet in a different case, CYG X-1, no definite periodicity in x-rays was found even though it was quite firmly identified with a spectroscopic binary system [Bolton (1972)]. In fact, CYG X-1 is the most observed of this group of sources since it is the brightest hard x-ray source in the sky. Its measured spectrum extends to several hundred keV [Matteson (1971); Mahoney (1973)] and its intensity fluctuates rapidly and erratically often by a factor of four or five [Holt et al. (1971); Agrawal et al. (1971)]. Now many astronomers are convinced that a collapsar (or "black hole") is the x-ray source in the CYG X-1 binary [Shakura and Synyaev (1973); Leach and Ruggini (1973)].

Various models have been suggested for these x-ray "stars" and usually the presence of collapsed objects -- white dwarf, neutron star, or collapsar (black hole) are invoked to explain the enormous energy outputs, since
collapsed objects possess strong gravitational and magnetic fields as well as high rotational velocity. A binary or multiple system involving a collapsed object was considered a viable model before any actual x-ray binaries were discovered [Hayakawa & Matsuoka (1964); Prendergast & Burbidge (1968)]. The theory proposed is that a strong gravitational force originating in a collapsed object causes continuous accretion of matter from the primary (normal) star toward the collapsed object. The accreting plasma acquires high velocity and reaches temperature of the order of $10^7 - 10^8$ °K, the resulting high temperature and shock wave then produce x-ray emission in combination with weak optical emission. A magnetized plasma compressed by accretion could also produce similar emissions [Bisnovatyi-Kogan and Fridman (1970)]. Therefore, the actual x-ray source is the x-ray and optical aureole formed around the collapsed object, but optically it is dim compared to its normal companion. Variability and flare-like phenomena in its emissions are expected [Pringle and Rees (1972)].

An alternative model proposed is a binary system consisting of two rotating magnetic stars (not collapsed objects) linked by a large magnetic flux [Bachall et al. (1973)]. The lack of co-rotation in the system would lead to twisting of magnetic field lines, hence increase of magnetic energy stored in the field until instabilities cause field lines to break and reconnect (magnetic shocks) and the stored energy to be released in the form of x-ray emission.
The available observational information shows that the intriguing characteristics of stellar x-ray sources cannot be readily explained by any simple model and it is doubtful that one model will be able to fit all the observed sources. Nevertheless, the knowledge on these special stellar objects has already helped tremendously in advancing the field of stellar evolution and in pulling the physics of collapsed objects out of a pure theoretical stage.

c) The Galactic Center

Although the concentration of interstellar dust has long prevented the central part of our galaxy from being visible optically, radio [Rougoor and Oort (1960)] and more recently infrared emission [Hoffman et al. (1972)] have revealed the existence of a nucleus (Sagittarius A). There appears to be a small radio source at the center of a flat disk and a ring of neutral hydrogen (HI), all embedded in an extended nonthermal emission region. Matter near this nucleus shows both high rotational velocity and rapid outward expansion. Although the detailed composition and structure is not known, it is believed that the galactic center is very possibly the site of recurring explosive events and the resulted continuous mass expulsion [Sanders & Wrixon (1974)].

X-ray observations also show an extended source at 2-20keV that encompasses the radio and infrared structure [Kellogg et al. (1971)] (Fig. 1.5, p.19). Named GCX, it could possibly be several unresolved sources, similar to the distributions in radio and infrared. Besides, within five
Fig. 1.5 The galactic center region as seen at different wave-lengths. The five x-ray sources are shown by their position (1σ error boxes) as given in the third UHURU catalog [Giacconi et al. (1973)]. Adapted from Hughes & Retallack (1973).
degrees of the center, there are at least four more discrete and probably compact x-ray sources, three also seen in hard x-rays [Bradt et al. (1971); Ricker et al. (1973a)].

In high-energy $\gamma$-rays (>10 MeV) there are conflicting but interesting reports on the galactic center: some data show an extended line (or disk) source that lies in the galactic plane [Kraushaar et al. (1972); Kniffen et al. (1973)], while other data indicated nothing more than several possible discrete sources [e.g. Browning et. al (1972)].

A most interesting measurement was the possible detection of mono-energetic $\gamma$-rays at 476 keV from the direction of the galactic center region [Johnson et al. (1973)], which has generated great interest and several theories concerning its origin [Borner et al. (1972); Fishman et al. (1972); Leventhal (1973); Kozlovsky and Ramaty (1974)].

d) Transient X-ray Sources

So far five "nova-like" x-ray sources have been reported [Harris & Francey (1968); Conner et al. (1969); Shukla & Wilson (1971); Matilsky et al. (1972); Ulmer et al. (1973)]. They are characterized by their sudden appearances, high peak intensities in soft x-rays and relatively short lives in terms of months. Despite the similarities between these transient x-ray sources and typical optical novae [Chodil et al. (1968); Evans et al. (1970)], there has been no optical identification, in particular, no optical novae have been found in the direction of the observed x-ray outbursts. Nevertheless, at least in the cases of the two
brightest ones, CEN X-2 and CEN X-4, their intensity and spectral variations are consistent with the model of an outburst of hot gases followed by isothermal expansion [Evans et al. (1970)]. Only for CEN X-4 there was a possible short (10 minute) but intense precursor x-ray burst 50 hours preceding the "nova" appearance, and no recurring appearance of any of these sources has ever been observed. 3U1543-47 is the least intense but stands out as it has the longest lifetime of almost two years.

Hard x-ray measurements for any of these sources are lacking except for some upper limits for CEN X-4 [Thomas et al. (1969)]. These sources are quite widely distributed in galactic latitude, with two located in the galactic plane. Although it is not clear whether they are indeed physically similar events, they are generally considered galactic objects [Silk (1973b)], yet it has been argued that one of them, 3U1543-47 might be extragalactic in origin [Sofia (1972)].

1.2.2 EXTRAGALACTIC X-RAY SOURCES

To this day nearly 20 previously known extragalactic objects have been found to be emitting at least soft x-rays. They include normal galaxies like M31 (Andromeda), the Magellanic clouds, all in the local group; giant radio galaxies like Cen A (NGC 5128) and Cyg A, Seyfert galaxies like NGC 4151, clusters of galaxies like those in Virgo and Perseus and a quasar 3C273. In addition, the UHURU satellite observed about 30 more relatively weak sources with locations
above 20° in galactic latitude (Fig. 1.2, p. 7). They are not yet identified with any known objects, but their number-intensity distribution show that they are more or less isotropically distributed. Therefore, they are believed to be extragalactic in location also [Kellogg (1973)]. It seems that x-ray emission is by no means an unusual phenomena in the observable universe. The observed sources are all but one (The Seyfert galaxy NGC 4151) the brightest (optically or in radio) or the nearest one in their own categories. The rest are not seen in x-rays probably because of the limited sensitivity and angular resolution of the detectors used. In addition, the level of the diffuse background might be the ultimate limiting factor. However, the background itself could very well have come from emissions of unresolved and distant sources [Setti & Woltjer (1973)].

The Megallanic clouds are close enough, only 50 kpc away, that x-rays are found to come actually from individual compact sources in them: four in LMC and an eclipsing binary in SMC [Giacconi et al. (1972); Schreier et al. (1972)]. Together with M31, they have rather consistent x-ray luminosities -- similar to that of our own galaxy; namely, in the order of $10^{39}$ erg/sec at 2 - 20 keV [Giacconi (1973)]. Therefore, x-ray emission of normal galaxies is believed to be collective emission of their constituent sources.

The giant radio galaxies, Seyfert galaxies, and the exploding galaxy M 82 are unusually active systems, and expectedly have enhanced x-ray emission. But in their own
classes, they show a wide range of x-ray luminosities (10^{41} - 10^{44} \text{ erg/sec}) and ratios of x-ray to optical luminosities (6 \times 10^{-3} \text{ to } 2 \times 10^2); all higher than those of normal galaxies [Giacconi (1973)]. The only quasar seen in x-rays is the closest one 3C273 and it has the highest x-ray output, 3 \times 10^{45} \text{ erg/sec in } 2 \text{ to } 20 \text{ keV}, of any known object. However, the nearest Seyfert galaxy (NGC 4051) is not observable in the same energy range. The nearest radio galaxy Cen A (NGC 5128) is not particularly luminous (6 \times 10^{41} \text{ erg/sec in } 2 - 20 \text{ keV}) but because of its rather hard spectrum, it has been measured positively up to almost 200 keV [Mahoney (1973)]. These facts are suggestive that x-ray emission from these systems is not produced in individual "stars", but by some other mechanism [Kellogg (1973)].

For even larger celestial systems, at least eight clusters of galaxies are found to be associated with luminous and extended x-ray sources [Kellogg (1973)]. The centroid of the emission region usually coincides with or is close to a giant active galaxy in the cluster. Good examples are the radio galaxy M87 in the Virgo cluster, the Seyfert galaxy NGC 1275 in the Perseus cluster and so on. The estimated dimensions of these sources range from 0.2 to 2.8 Mpc, and their x-ray luminosities in 2 - 20 keV from 7 \times 10^{43} \text{ to } 5 \times 10^{44} \text{ erg/sec}, higher than that of any single object except the quasar 2C273. There are no definite low-energy cutoffs in their x-ray spectrum and this seems to suggest that these sources are not collective emissions from groups
of galaxies. Competing emission mechanisms for these sources are thermal bremsstrahlung from hot intergalactic gas in a cluster and [Solinger & Tucker (1972)] inverse Compton scattering of the universal microwave background by relativistic electrons in the system [Harris (1974)]. Hard x-ray measurements of these sources which are important in precise determination of spectral characteristics and hence emission mechanisms, are either nonexisting or not good enough [Peterson (1973)].

1.2.3. DIFFUSE COSMIC BACKGROUND

Because of the possible cosmological significance of the diffuse high-energy photon background [Silk (1970); Setti and Rees (1970); Cowsik (1973)], a wealth of spectral data have been produced by means of various experimental methods, all the way from 1/4 keV up to more than 100 MeV. Fig.1.6, (p.25) shows some generally accepted and some more recent measurements [Pinkau (1973)]. Although there are still uncertainties in several energy ranges, it is very probable that the spectrum cannot be fitted with a single representation, such as a power law, throughout the whole energy range [Silk (1973a)]. In addition, partly due to presence of galactic contributions, the isotropy of the diffuse flux is not equally well established at different energies. Therefore, it is best to discuss separately the following energy intervals: a) 1 - 20 keV Rocket-borne proportional counters have rather consistently shown that in this region the energy spectrum could be represented by a power law with the smallest index (α_E=0.5). Within a precision of around 10%, the
Fig. 1.6 The energy spectrum of the diffuse background in x-rays and γ-rays, as measured by different experiments. The part of cosmic component is taken from Pinkau (1973), galactic component from Silk (1973).
observed flux is isotropic, with a possible exception at the low-energy end [Felten (1972)]. There is also a possible evidence that a spectral line is present near 6-7 keV [Shulman et al. (1971)]. b) 20 keV-500 keV Data in this region are mostly obtained from balloon-borne scintillation detectors, and seems to show a power law index different from the lower energy region [Silk (1970)]. A spectral break or a gradual change in exponent might occur between 20 and 40 keV [e.g. Schwartz et al. (1970)]. But because of questions on the effect of atmospheric scattering on balloon data [Makino (1970)] and induced radioactivity on satellite data [Dyer and Morfil (1971)], it is also argued that a single spectral index (aE^{-1}) could possibly fit the entire 1-100 keV energy range [Kasturirangan and Rao (1972); Dennis et al. (1973)]. Available data shows that up to 100 keV, the flux is isotropic to within 5% away from the galactic plane [Schwartz (1969)]. c) 500 keV - 10 MeV In this experimentally difficult range, data come from diversified sources and show considerable conflict [Pal (1972)]. A possible excess of flux over a power-law extrapolation from lower energies seems to be supported by γ-ray measurements above 20 MeV. Yet some observations show no excess at all up to 8.5 MeV [Golenetskii et al. (1971); Daniel et al. (1972)]. Until the (precise) spectral shape over this energy range and above is known, it does not seem useful to choose among the multitude of proposed theories to interpret the uncertain excess.

Possible contributions from the galactic plane in
different energy intervals are shown by cross-hatched areas in Fig. 1.6 [Silk (1973)]. It becomes more competitive with the isotropic flux as energy increases and the two are almost the same in the γ-ray energies. But it is not yet clear whether it is a real diffuse galactic flux or comes from unresolved discrete sources.

Because of its diffuse nature, the cosmic background will invariably be seen by all x-ray and γ-ray telescopes, with its contribution proportional to the size of the telescope aperture. For instance, as is shown in Fig. 1.4 (p.15), the spectrum of the diffuse cosmic background seen by a detector-telescope having a typical aperture of 0.1 steradian (angular FWHM = 10°) lies between the spectra of CYG X-1 and the Crab pulsar, NP 0532. This is comparable to the intensity of most of the strong sources in the energy range 10 - 100 keV, thus limits the ability of telescopes with apertures of this size to detect weaker sources.
CHAPTER II

INTRODUCTION II: THE SCIENTIFIC PROBLEM

2.1 ON BALLOON-BORNE OBSERVATIONS

As has been shown in previous sections, for the understanding of the nature of an x-ray source and the responsible emission mechanisms, a good knowledge of its intensity, energy spectra, spatial and temporal structures over a wide energy range is essential. For instance, measurements over more than two decades of energy are usually needed to determine precise spectral form, power law, or exponential in most cases. Besides, spectral characteristics at higher energies could differ considerably from a simple extrapolation from the low energy data, as are illustrated in the cases of SCO X-1 (Fig. 1.4, p.15) and the diffuse background (Fig. 1.6, p.25).

With various intrinsic limitations, such as observation time, payload, direction control, power capacity, and the level of background radiation, rocket and satellite-borne telescope-spectrometer have so far provided useful data mainly in the energy range below about 50 keV. Photons with energy above 15 keV can penetrate three or more gm/cm$^2$ of the atmosphere, to an altitude readily reachable by today's large-volume stratospheric balloons carrying larger payloads, typically several hundred pounds, than that would usually be allowed on rockets or satellites. Therefore, balloon-borne
experiments have been largely responsible for extending the studies of cosmic x-rays and γ-ray observations. No less than 20 x-ray sources have been observed from balloon altitudes.

More freedom in design enables more sensitive detectors and various observation techniques to be utilized with reasonably long observation time, typically 10 hours, and sometimes up to three days. The recent development of round-the-globe superpressure balloon flights has promised observation times of 30 days or more.

Additional advantages of balloon experiments are shorter preparation time, lower cost, and retrievability of instrument, which enables repeating observations with improvements when necessary.

The major problem that confronts balloon-borne detectors is the radiation environment at floating altitudes. The atmosphere is not only an absorber, but also itself a source of radiation — cosmic-ray induced secondary particles and photons of a wide range of energies (A detailed discussion of atmospheric secondary radiation will be provided in Appendix C, p.182) that together with primary cosmic radiation produce collectively an everpresent background in a detector against which the comparatively weak extraterrestrial photon signals are to be measured. This atmospheric background is diffuse in nature while the photon signal could either be semi-diffuse (from only above the atmosphere), as for the cosmic diffuse component, or parallel beams in cases of discrete
sources at large distances.

The sensitivity of a detector or its ability to measure the signal is proportional to

$$\sqrt{\frac{AT}{B}}$$

where $A$ is the active area (or geometrical factor) of the detector,

$T$ is the observation time exposed to the signal, and

$B$ is the background level.

While $A$ and $T$ have their limits, it is important that $B$ be kept small.

In order to suppress the effect of the atmospheric background, various shielding techniques have been used to provide the detector with a defined aperture of detection, thus forming a telescope. A schematic representation of a hard x-ray (or soft γ-ray) telescope-spectrometer in Fig. 2.1, (p.31), shows the various parts of instruments utilized in balloon observations.

Part A is the central or main detector, i.e. the spectrometer, responsible for the desired measurement. It could be either a gas proportional counter, a scintillation counter or a solid-state detector. Proportional counters filled with high-Z noble gas (krypton or xenon) have good energy resolution but detection efficiency is too low above 50 keV, though large sensitive area is possible [e.g. Brisken (1973)]. For crystal scintillation counters such as NaI(Tl), adequate energy resolution as well as good detection efficiency is achievable up to the MeV range; and they are
Fig. 2.1 A schematic representation of the composition of a telescope-spectrometer in x-rays and low energy γ-rays.
therefore widely used [e.g. Peterson (1972); Johnson et al. (1973)]. Solid-state detectors could provide superior energy resolution but have a small active volume and the needed large cryogenic packages limit their usefulness (e.g. Jacobson (1968); Womack and Overbeck (1970)].

Part B is for shielding against radiations coming toward the bottom of the main detector. It could be passive* or active ** [e.g. Womack and Overbeck (1970)] or a combination of both — usually the passive part as photon shield and the active part as charged particle shield. [ e.g. Bingham and Clark (1969); Agrawal (1972)].

Part C usually serves two purposes: shielding against atmospheric radiation from the side directions as well as being a part or the whole of a collimator to define the aperture or acceptance angle of the telescope. It could also be either passive [Webber and Reinert (1970)] or active [Peterson et al. (1972); Womack and Overbeck (1970)] or a combination of both [Agrawal (1972)].

Oftentimes Part B and Part C are combined to form a one-piece "cup-shaped" shield, particularly when both are

* A passive shield is an absorber made of high-Z material (lead, tungsten, tin, brass, or their combination) to stop or attenuate radiation.

**An active shield is usually a scintillation detector of a particular shape to detect undesirable but penetrating radiations so that the detection of these same radiations in the main detector could be vetoed by means of electronic anti-coincidence.
active [e.g. Johnson (1972)]. This is an effective but usually expensive shielding method.

Part D is either a thin active charged particle shield [e.g. Johnson (1972)] or a removable aperture shutter, passive or active, for the purpose of measuring the detector background [e.g. Bleeker et al. (1968)].

Part E is a fine collimator for defining small acceptance angles. It could be either passive [e.g. Agrawal (1972)] or active [e.g. Anderson (1972)] and is an important element when good angular resolving power is needed for the telescope.

The dimensions and configuration of an actual telescope-spectrometer depends on its purpose and energy range of measurement. But an important consideration is the optimum design of shieldings.

The efficiency of absorption (attenuation) or detection of photons by any shielding or detector of thickness is proportional to

$$(1 - e^{-\mu t})$$

where $\mu$ is the absorption or interaction coefficient of the material that constitutes the shield or detector. (A detailed discussion of photon-matter interaction is given in Appendix B, p.178). But the same mass that attenuates or detects the desired radiation will also cause both primary and secondary radiation to interact in other ways that result in local production of undesirable radiation and contributes to the background of the instrument. This kind of production increases
with the sizes of shields or detectors. Even totally active shielding can at best detect only part of the radiation produced within it and thereby perform the veto function. Therefore, thicker shielding does not always mean lower background. For reasons not well understood, the actual background usually turned out to be higher than expected even in cases where careful calculations have been done. It is a complicated combination of leakage through shielding and local production [Kasturirangan (1971); Peterson (1972); Mahoney (1973)]. The challenge in balloon x-ray experimentation has been to reduce as much as possible such background and provide better sensitivity of measurement.

However, the flux of primary cosmic rays and hence the level of atmospheric secondary radiation, both particles and photons, decreases with decreasing geomagnetic latitude or increasing geomagnetic cutoff (A more detailed discussion is provided in Appendix C, p.182). It is well known that a given detector flying at a site of lower geomagnetic latitude has lower background [Bleeker et al. (1970); Daniel & Stephens (1974)].

Therefore, an effective shielding design together with the suitable choice of flight site will contribute to good sensitivity of observation.

2.2 THE SCOPE AND OBJECTIVES OF THE EXPERIMENT

Just like the situation in optical astronomical observation, geographical as well as socio-economic factors
have caused the concentration of cosmic x-ray observational activities in the northern hemisphere, balloon experiments in particular. Yet the central part of the galactic plane containing the majority of galactic x-ray sources, including the galactic center, lies in the southern sky. Many interesting and important sources, within the stretch from galactic latitude 250° onward through the galactic center region, are beyond the reach of observations from any location in the northern hemisphere, not to mention sources like those in the Magellanic clouds (Fig. 1.2, p. 7). The comparatively few observations performed in the southern hemisphere have provided interesting results (for instance, 70% of all the hard x-ray source so far observed) and yet the accumulated data is limited and sporadic [e.g. Lewin (1968); Davison et al. (1971); Mahoney (1973); Ricker et al. (1973a)]. Some of the discoveries would need independent experimental confirmation [Johnson et al. (1973)].

The general objective of this experiment was to design and build a balloon-borne x-ray telescope-spectrometer with good sensitivity as well as reasonable angular resolution in an extended energy range, namely 17 keV to 1.5 MeV, in which data for many sources are lacking; and to utilize the system to observe the southern sky from a suitable location in the southern hemisphere, where a large number of interesting sources would be accessible.

The specific objectives are the following:

a) To measure the intensity and energy spectrum above
17 keV of sources known in this energy range or lower, along
or near the galactic plane from $l^{\text{II}} = 300^\circ$ onward through the
galactic center to $l^{\text{II}} = 30^\circ$.

b) To detect any source unknown previously, perhaps
new transient sources.

c) To measure any possible diffuse emission from:
the galactic plane.

\*\*\* $l^{\text{II}} = \text{galactic longitude (1950)}.$
CHAPTER III

INSTRUMENTATION

3.1 THE SPECTROMETER-TELESCOPE

3.1.1 DESIGN CONSIDERATIONS

The underlying philosophy in this experiment is that the detector system being designed and built should be relatively simple, light weight and low cost, yet capable of performing well in achieving our experimental objectives set forth in the preceding chapter. Simplicity means that the various components could be readily built and/or assembled with available manpower and facilities in the laboratory; and more importantly, it means reliability during flight operation. Light weight would enable the system to be flown to higher altitude without the necessity of using the extremely large volume balloons that are both expensive and unreliable. Both simple design and low cost would enable efficient yielding of scientific information by continuous development in experimentation.

Following a successful design approach in a previous experiment of rather limited energy coverage, namely 25-700 keV [Webber and Reinert (1970)], two similar large area NaI (Tl) scintillation detectors are placed in a "back-to-back" configuration with one as the main detector (or
spectrometer) which faces the front aperture. By an anti-coincidence between these two elements, the spectrometer will have a high front-to-back photon detection sensitivity ratio; and together with passive collimation and side shielding a photon telescope is formed. Charged particle rejection is achieved by pulse height discrimination in the main detector, anticoincidence with the back detector, and an additional active charged particle anticoincidence shield on the side.

The actual configuration of the detector system is shown in Figure 3.1(a) (p. 39) and (b) (p. 40) and each element will be discussed in the following section. Thallium activated sodium iodide detectors are used because of their high photon detection efficiency, high light output and good energy response linearity over the energy range of interest. Commercial availability of large area NaI(Tl) detector is another factor. The large area will in effect provide good sensitivity and allow scanning observations, i.e. distribute observation time to more sources in the limited duration of a balloon flight.

3.2.2 DESCRIPTION OF THE SPECTROMETER-TELESCOPE

As is shown in Figures 3.1(a) and (b), the spectrometer-telescope consists of five parts: the spectrometer, the guard detector, the graded photon shield, the charged particle shield and the collimator.

a) The Spectrometer (Main Detector) -- It is a 10-inch by 1.425 inch (25.4 cm x 3.6 cm) NaI(Tl) scintillation crystal
Fig. 3.1(a) Cross-sectional view of the Mk. III telescope-spectrometer showing two half cross-sections separated by 45°. The left side shows the photomultiplier tube viewing the spectrometer and the right side shows the photomultiplier tube viewing the plastic charged particle shield.
Fig. 3.1(b) Top view of the Mk.III telescope-spectrometer.
hermatically sealed in a special aluminum housing. The front surface is covered by an 0.020 inch thick aluminum window which is transparent for photons down to 15 keV. The crystal has a surface area of 500 cm², but an aluminum flange on the front edge has limited the sensitive area to 450 cm² for lower energies. The crystal housing has four quartz windows on the side through which four 1.75 inch RCA 7151N photomultiplier tubes are used to view the crystal. This configuration optimizes the "two crystal back-to-back" design, but limits the size of the phototubes utilized to view the main detector, and thus the total photocathode area. As a result, the energy resolution of the spectrometer, which depends strongly on photoelectron statistics, is less than ideal due to the smaller light collection efficiency. The energy resolution measured in the laboratory in terms of FWHM (full width at half maximum) at various energies is shown in Fig. 3.2, (p.42). The points given by available monoenergetic γ-rays shows that the normal E⁻¹/² dependence is well followed.

Detection and measurement of high energy photons, like x-rays (above 10 keV) and γ-rays depend on their particle-like behavior that leads to interaction with the detector medium and deposition of energy in the process. Three well-known processes provided the needed interaction, i.e. photoelectric effect, Compton scattering, and pair production (A detailed discussion of these processes will be given in Appendix B, p.178). Their absolute and relative probabilities of occurrence depends on the energy of the interacting photon
Fig. 3.2 Energy Resolution in terms of percent FWHM of the spectrometer as calibrated by monoenergetic gamma rays from radioactive isotopes. Data points from laboratory tests (Durham) and preflight check (Parana) are shown. The dash line indicates the theoretically expected functional dependence.
as well as the detection medium. As can be seen in Fig. 3.3 (p.44) which shows the cross sections of all three processes in sodium iodide, only photoelectric effect and Compton scattering need to be considered in the energy range of 17 keV to 1.5 MeV. Below 250 keV, the latter becomes more important and yet the total cross section drops rapidly. The total interaction probability decreases by a factor of a hundred over the approximately two decades of energy stretch.

When both processes are taken into consideration, the 1.425" (3.6 cm) thickness of the spectrometer represents at least one interaction length* up to 600 keV, and about 0.6 interaction length at 1.5 MeV, as can be seen in the calculated total interaction efficiency (as a function of energy) in Fig. 3.4 (p.45). The total interaction efficiency is related to the total interaction cross section \( \tau_{\text{total}} \) (Fig. 3.3, p.44) by

\[
(1 - e^{-1.6 \text{~cm})} \tau_{\text{total}})
\]

when normal incidence is assumed and is hence a simple function of the detector thickness for a given photon energy. But as will be shown later (cf. Section 5.1.3(c), p.82), a more important parameter is the photopeak efficiency (also shown in Fig. 3.4, p.45), which is the probability of total absorption of a normally incident photon by the detector.

*An interaction length is defined as the distance in matter across which a parallel photon beam will suffer an e-folding (~65%) loss in intensity because of photon matter interactions, which in this case are photoelectric effect and Compton scattering.
Fig. 3.3 The interaction cross-sections of high-energy photons in NaI crystal for collimated photon beams.
Fig. 3.4 The calculated total interaction and photopeak efficiencies of the spectrometer for collimated photon beams at normal incidence.
Since total absorption can be caused by either photoelectric effect or multiple Compton scattering, the photopeak efficiency depends on both thickness and lateral dimension of the detector. Although no analytic relation exists, generally the photopeak efficiency increases as either dimension increases [Miller et al. (1958)].

An important aspect is the photopeak linearity of the detector energy response. Figure 3.5 (p.47) shows the result of in-laboratory calibration using standard monoenergetic $\gamma$-rays from radioisotopes. One possible problem associated with a large detector viewed by a limited number of phototubes is the uniformity of response over the sensitive area. By using collimated radioactive sources that allowed monoenergetic photons to enter the detector in a circular area of a diameter approximately 0.75 inch, energy response over the 450 cm$^2$ area is found to be uniform to within 5%.

b) The Guard Detector — It is a 10 inch by 1.5 inch (25.4 cm by 3.8 cm) NaI(Tl) crystal in a regular housing with a 10 inch optical window at the bottom. The insertion of a cone-shaped white diffuse chamber allowed the large crystal to be viewed through the optical window by a 5 inch EMI 9530 photomultiplier tube.

The function of this detector is to shield against atmospheric $x$-rays, $\gamma$-rays, and charged particles that come toward the back of the spectrometer. $X$-rays will be stopped while most gamma rays will either be stopped or produce a signal in this detector by Compton scattering; so that if
Fig. 3.5 The energy calibration curve of the spectrometer, established by using monoenergetic gamma rays from radioactive isotopes. Extrapolation to low energies has incorporated nonlinearity in the response of NaI(Tl) as given in Birks (1964).
the scattered photon is detected in the spectrometer, the event can be discarded by anticoincidence between the two detectors. In the reverse case, a photon that has first a Compton scattering in the spectrometer may end up being detected in the guard detector and this event will also be discarded. This will help to reduce the undesirable Compton contribution in any photon spectrum to be measured by the spectrometer.

c) The Graded Shield -- This is a cylindrical shell of 10 inches in height and 12 inches inside diameter, and constructed of three coaxial layers of high-Z metals: 1/4 inch of lead (Pb), 1/32 inch of tin (Sn), and 1/64 inch of copper (Cu). Together the thickness represents at least one attenuation length up to about 550 keV but effectively more because most of the photons will hit the shield at an angle and traverse paths longer than the nominal thickness.

Having high density as well as high mass attenuation coefficient, lead is the most effective and hence the most often used shielding material, but the K fluorescence x-rays from lead, an inevitable product of absorption of high energy photon and interaction with charged particles, lie inside of the energy range of the spectrometer (87 keV) and give rise to a potential background problem. As can be seen in Figure 3.6, (p.49), the tin and copper layers have successively lower characteristic x-ray energies, 29 keV and 9 keV respectively. The purpose of the graded shield is to use lead as the dominant absorber, while arranging the three
Fig. 3.6 The x-ray absorption edges of lead, tin, and copper as shown in their mass absorption coefficients as a function of photon energy.
metallic layers in such an order and thickness that the fluorescence x-rays will be gradually shifted to below the lower energy threshold of the spectrometer, i.e., \(^{\sim}17\) keV.

d) The Charged Particle Shield — This is a cylindrical shell made of 1 inch thick NE 102 plastic scintillator. Its 10 inch height and 12.5 inch inside diameter enables it to fit tightly outside of the graded photon shield and offer geometrically the same shielding coverage on the spectrometer. The scintillator is polished on all sides, housed in an aluminum can with highly polished internal surfaces, and viewed by four 2-inch EMI6097 photomultiplier tubes at the bottom end. Optical coupling is established between the scintillator and the photocathodes where they meet. Reflection at the inside surfaces of the can enhances transmission of scintillation light so that the phototubes can "see" very well all parts of the scintillator. By using radioisotope \(\gamma\)-rays, response of the various parts of the detector were found to be rather uniform although good uniformity is not required for the purpose of the detector. The plastic scintillator is capable of detecting charged particles with practically 100% efficiency while most x-rays and \(\gamma\)-rays will readily penetrate or at most be Compton scattered in the 2.54 gm/cm\(^2\) of hydrogenous material. It can help to recognize not only events produced by charged particles that go through the side shielding and deposit energy in the spectrometer within the 17 keV to 1.5 MeV range, but also prompt \(\gamma\)-rays produced in interaction in the graded shield or any inert material by charged
particles that go through the plastic scintillator first.

51

\textbf{e) The Collimator}—Located on top of the spectrometer, it is composed of 1/32 inch thick brass slates (sheets) in an egg-crate structure, as is shown in Figure 3.1 (a) and (b) (p.39 and 40). It is six inches in height and covers the same surface area as the spectrometer. Each "cell" is rectangular in shape and defines a rectangular geometrical aperture of 6° x 10° in half angles. It collimates by absorption of photons incident at angles other than the defined aperture. Brass is composed of mostly copper, and therefore, its fluorescence x-rays are below the lower energy threshold of the spectrometer, as has been discussed in part c) in this section.

The angular response of the telescope to a distant point source was measured in the laboratory in a simulated condition using radioactive sources. The one-dimensional results up to 600 keV are shown in Figure 3.7 (p. 52). As is expected, while at low energies (<80 keV) the angular response shows a 6° FWHM, the aperture of the telescope gradually opens up as energy increases.

3.2 THE ELECTRONIC SYSTEM

The electronics associated with the spectrometer-telescope is shown in a block diagram in Figure 3.8 (p.53). It is designed to perform the following:

\begin{itemize}
  \item[a)] To condition the detector signals for processing
  \item[b)] To define the energy range of detection in every detector, e.g. 17 keV to 1.5 MeV in the spectrometer
  \item[c)] To realize the function of the shielding detectors
\end{itemize}
Fig. 3.7 One-dimensional (azimuthal) angular response of the telescope as measured at four different energies in the laboratory.
Figure 3.8
by selecting events in the spectrometer that are not in anticoincidence with the signals from any other detector.

d) To digitize (analyze) the pulse-height of the selected spectrometer events

e) To properly format and telemeter each analyzed event in real time, and

f) To continuously monitor and telemeter the various counting rates as well as auxiliary information such as system temperature and so on.

Outputs from detector photomultiplier tubes in the form of pulses generated by detection of a photon or a particle, are first summed (for detectors with more than one phototube), properly shaped and amplified. Then a set of four adjustable level discriminators determine the minimum pulse height (corresponding to lower energy limit) from each detector and the maximum (corresponding to the upper energy limit) from the spectrometer to be used for logic control. Pulses representing energy deposits $E$ of $17 \text{ keV} < E < 1.5 \text{ MeV}$ in the spectrometer, $E > 20 \text{ keV}$ in the guard detector, $E >$ half the minimum ionization of a normally incident particle in the charged particle shield will pass and generate discriminator gates. The widths of the gates are fixed and correspond to blanking times determined by considerations on the original pulse duration.

A relativistic charged particle traversing the spectrometer will deposit about $1.3 \text{ MeV}$ of energy per gm/cm$^2$ of NaI along its path and therefore at least $17 \text{ MeV}$ (1.425
inch equals to 13.28 gm/cm²) in passage, thus produce a large and long pulse. It has been reported that in large alkaline halide detectors such a huge pulse is accompanied by a string of after-pulses, up to 100 keV in equivalent energy, superimposed on the falling tail of the event. This after-effect could last as long as 100 μsec [Frost et al. (1966)]. Therefore, the high level (>1.5 MeV) discriminator gate was given a long gate length (blanking time) of 47 μsec so that such afterpulses will not be accepted for digitization as legitimate photon events. The discriminator gates are fed into the LOGIC CONTROL -- an anticoincidence circuit formed by a set of NOR and NAND circuits and gate-forming monostable vibrators. The LOGIC CONTROL determines whether an event from the spectrometer is in the 17 keV to 1.5 MeV energy range and whether it is not in coincidence with any event in the shielding detectors within resolving times, depending on the gate lengths associated with the individual detectors. When the requirements are met, control gates will be sent to activate the ADC (analog-to-digital converter) and scalers so that the event will be accepted for pulse-height analysis. For this purpose, the properly shaped output of the spectrometer for the given event, in the form of a bipolar pulse, are fed simultaneously to the 8-bit ADC, which uses single-slope integration to provide serial output of an 8-digit binary number that characterizes the event. The ADC is set up such that the number 256 represents the highest energy to be measured, i.e. 1.5 MeV. Thus we have a 256-channel PHA
(pulse-height analyser) with an average channel width of approximately 6 keV. Each of the resulting binary numbers will be "tagged" in front by a 6-digit binary SYNC word (for identification purpose) to form a 14-digit binary event word which will be transferred, by using shift registers, to a PCM (pulse code modulation) data channel.

The PCM data train has a bit rate of $10^4$ bits sec$^{-1}$ and hence 1.4 msec is required in the shifting of each 14-digit binary event word into this data train. Compared to the 157 &mu;sec deadtime generated for the analysis of each accepted event by the ADC, the 1.4 msec shifting time contributes most to the system deadtime and imposes an upper limit on telemetry rate to 714 events sec$^{-1}$. The system deadtime increases with the rate of accepted events (cf. Fig. 5.3, p.83).

The TIMING CONTROL circuit programs and controls the proper timing of all electronic functions described above.

In addition, a total of four event counting rates are monitored and telemetered. It is achieved by feeding the low level discriminator gates associated with the three detectors and the coincidence gate in the LOGIC CONTROL into rate scalers. These gate rates are scaled down by a factor of 256 and sampled sequentially by a sequencer circuit, each for 52.4 seconds.

The FM-FM telemetry transmits the PCM data, the count-rate samples, the magnetometer outputs, and system temperature in separate subcarriers which are mixed and put on a main carrier at a P-band frequency of 277.7 MHz.
3.3 **Auxiliary Systems**

A pair of horizontally and orthogonally mounted flux gate magnetometers are used to measure the azimuthal aspect of the telescope with respect to the local geomagnetic field direction. The voltage outputs of those magnetometers are sinusoidal functions of the geomagnetic azimuth and are 90° out of phase with each other, hence can be used to determine the pointing direction of the telescope unambiguously.

A temperature sensor is located in between the telescope and the electronics to monitor temperature in the system.

The telescope-spectrometer, the electronic system, and the magnetometers are all housed in a cylindrical aluminum gondola which is pressurized to one atmosphere and is thermally insulated with plastic foam material. The hemispherical top of the gondola has a thin portion (0.020 inch thick) which covers the aperture of the telescope in order to minimize the passive absorption of low energy x-rays by the gondola.

A rotator consisting of a d.c. motor and a clutch assembly is used to orient the whole gondola which is to be suspended at an angle under the rotator by steel cables, (cf. Fig. 4.1, p. 61).

Silver-zinc batteries carried inside the gondola supply the power required for the functioning of all systems during a balloon flight.
CHAPTER IV

THE BALLOON FLIGHT

4.1 ADVANTAGES OF THE FLIGHT LOCATION

For balloon experimentation in the southern hemisphere, Australia has been the traditional flight station, but its distance from the United States is always a major drawback. Logically attention was turned to South America, for both scientific and economic reasons. Since 1969, a cooperative program was set up between the United States and Argentina to conduct balloon flight from Parana (31°36'S, 60°31'W) in northern Argentina. Annual expeditions, arranged and supported by the National Center for Atmospheric Research and participated in by various scientific groups from the states, proved to be very successful and productive [Haymes (1971)].

First of all, the city of Parana is located at (-31°36') in geographical latitude. Therefore, the galactic center (declination = -29°) will have an almost overhead transit every day. The galactic plane between \( \ell^I = 210° \) and \( \ell^I = 40° \) (through the center) and the concentration of x-ray and γ-ray sources will be less than 40° from zenith during transit, hence readily accessible to observation with minimized atmospheric absorption (cf. Fig. 4.6, p. 70, and Fig. 6.1, p. 92).
Secondly, the geomagnetic field has such a configuration that in this region, the cutoff rigidity for primary cosmic ray is unusually high, 11.7 GV, and the line of zero magnetic variation lied just west of Parana [Chernosky and Maple (1960)].

As has been discussed briefly in Section 2.1 and in detail in Appendix C, the high geomagnetic cutoff rigidity means a more favorable radiation environment at balloon altitude — resulting from the lower fluxes of both primary and secondary particles and atmospheric photons. This leads to an enhanced sensitivity for the instrument.

The small magnetic variation near this location simplify the interpretation of aspect information of the telescope, as provided by magnetometers. Real-time monitoring of the telescope pointing direction could be achieved with good accuracy by simple visual inspection of magnetometer readouts — a convenience for guiding the telescope by ground command.

All of these characteristics of Parana are favorable to our experimental objectives. Actual flight operation and experimental results have justified our expectations.

4.2 **FLIGHT OPERATION**

The balloon flight (designated NCAR 68-N) of the Mk. III x-ray telescope-spectrometer took place on November 22, 1971, as part of the NCAR Argentine Expedition named "Galaxia '71". The UNH scientific package weighed 305 lbs, including the gondola, and was flown on a Winzen 10.6 million cubic feet balloon constructed of 0.7 mil polyethylene
film. The NCAR flight equipment included a 46 foot parachute, 150 pounds of ballast, and a balloon control package consisting of:

1) a barotransmitter which provides pressure altitude data from launch to termination of flight,
2) a Rosemount pressure gauge for more precise measurement of atmospheric pressure smaller than 10 mb with an accuracy of \( \pm 0.1 \) mb,
3) receiver and decoder in the command system for ballast drop, cutdown and for our experiment: ground controlled inflight rotation of the telescope package,
4) a Rawinsonde package which provides continuous air temperature readings and radio beacon signal for GMD* and aircraft balloon tracking,
5) a safety timer for automatic cutdown in case of failure of command system.

The complete payload added up to a weight of 678 lbs. and was arranged in a configuration shown in Fig. 4.1 (p. 61). The purpose of the arrangement is fourfold:

1) to allow the telescope to have an unobstructed view regardless of its azimuthal position with the fixed zenith angle 29.5°,
2) to avoid additional load on the telescope rotator,
3) to provide the necessary stability for the telescope as well as the rest of the system,
4) to keep the other packages as far away from the

* Meteorological Radio Theodite
THE BALLOON FLIGHT TRAIN

Figure 4.1
telescope as possible in order to minimize the possibility of radiation production in added local mass.

After a preflight checkout of all systems through telemetry link, the instrument was launched smoothly into clear sky at 0914 UT (0614 LST*). At launch all detectors and auxiliary systems were activated and continuous telemetry contact was established between the instrument and ground station.

The block diagram in Fig. 4.2 (p. 63) shows the detailed setup of the ground station which performed the following functions from launch to landing:

1) to monitor in real time instrument outputs that are relevant to functioning of the telescope system; namely, magnetometer readings, telescope counting rate in channels 1 to 7 (17 - 40 keV), atmospheric pressure, temperature inside the gondola, and balloon location,

2) to use the radio command system to control the orientation of the telescope for selective scanning of regions of interest in the sky,

3) for subsequent data analysis, to record on video tape the telemetered outputs of all instruments, together with accurate timing signals generated by a clock on the ground. At the same time PCM data was decoded and put on digital tape.

The balloon followed a normal ascent and reached float at an altitude of 133,600 feet (2.58 mb) at 1142UT

*Local Standard (Civil) Time
TELEMETRY RECEIVER (277.7 MHz)

D A T A T I M I N G M A R K E R S

C O M M A N D T R A N S M I T T E R

c c

w  cd

w a :

t c  o

a  e - i

<  <

u

z

CD ih

D E

CD M

o :

E u

fa CD

M

s a

f a

PC M D A T A T E M P E R A T U R E

M A G I

M A G I I

P R E S S U R E

V I D E O M A G N E T I C T A P E R E C O R D E R

M I X E R

1Hz

10k Hz

D I G I T A L R E F E R E N C E C L O C K

10kHz

PCM COMMAND ENCODER

COMMAND TRANSMITTER

PCM DATA

TEMPERATURE

MAG I

MAG II

PRESSURE

VIDEO MAGNETIC TAPE RECORDER

OSCILLOSCOPE

COUNTER

COUNTER

LON CHANNEL RATE METER

DIGITAL MAGNETIC TAPE RECORDER

STRI P C H A R T R E C O R D E R

OSCILLOSCOPE

GROUND STATION

Figure 4.2
(0842 LST) and remained for about 8 1/4 hours within the range of pressure altitudes 2.3 to 2.7 mb until flight termination by aircraft command at 1958UT (1658LST) (Fig. 4.3, p. 65, and Fig. 4.5, p. 68). The parachuted payload landed 43 minutes later about 200 miles west by southwest of Parana. Surface wind at the impact site caused the packages to be dragged by the open parachute for some distance in the field. As a result the crash ring was bent out of shape and the gondola was punctured near the top. The can for the plastic detector was therefore broken but the rest of the system survived and performed normally in the subsequent afterflight checkout.

4.3 INSTRUMENT PERFORMANCE AND OBSERVATIONS

Throughout the 11-hour flight, all systems performed quite well. The drift of the balloon in geomagnetic latitude and in altitude probably caused part of the slight changes in background counting rate. Temperature in the gondola varied within the range of 22°C. to 28°C. and caused some drift in the noise level of the main detector PMT's and hence counting rate in the lowest channels. In flight energy calibration was provided conveniently by the atmospheric electron-positron annihilation line at 0.511 MeV, which is shown together with the atmospheric continuum background obtained at float altitude in Fig. 4.4 (p. 66). Subsequent data analysis on this γ-line feature showed that gain of the NaI spectrometer has not changed beyond 5%. The time history of various important parameters as well as background
The horizontal trajectory of the balloon flight is shown with time marks (Universal Time). Geomagnetic cutoff lines (heavy broken lines) are estimated from data given by Quenby & Wenk (1962). Lines of equal magnetic variation (fine broken lines) are taken from aeronautical charts.
Fig. 4.4 The background count-rate spectrum of the spectrometer at a typical floating altitude as obtained from a 10 minute accumulation. The atmospheric 0.511 MeV annihilation line is also shown with continuum subtracted. Also shown is the division of channel intervals in subsequent data analysis.
levels during the flight are shown in Fig. 4.5 (p.68).

One annoying problem present was the proximity of the transmitting and receiving antennas at the ground station. When command signals were being sent, noise bursts appeared simultaneously in the telemetry signal. A preamplifier between the receiver antenna and the receiver should have been removed but was not done in time. However, this problem only caused some uncertainty in a few percent of the data. Between 1516 UT and 1526 UT, a large increase in counting rate was noticed and it was later found out to be caused by an energetic solar flare of class 2B*.

Since the balloon local magnetic variation along the flight trajectory (Fig. 4.3, p.65) never exceeded 2°, the telescope aspect (azimuth) was conveniently determined by visual inspection of the two magnetometer readouts which were put on a strip chart recorder. Calibration of the magnetometers was achieved by making a complete rotation of the telescope in azimuth and it was done five times during the flight. There was no appreciable intrinsic balloon rotation or payload oscillation. Radio command control of the telescope rotation was generally successful except on several occasions when repeated command signals had to be sent to obtain the desired response. It was believed to be caused by eclipsing of the receiving antenna in the NCAR package by the telescope gondola.

*Account of measurement of the solar event by this experiment was reported in the 1972 Meeting of the Solar Physics Division of AAS, University of Maryland, April, 1972.
Fig. 4.5 The flight record of various important parameters.
By the successful radio command operation, an optimized observation program was achieved. The program in terms of constellations is listed in Table 4-1, (p.70 ). Also shown in Fig. 4.6, (p. 71), are the actual scanning trajectories of the telescope during the balloon flight.
### Table 4.1
**OBSERVATION PROGRAM**

<table>
<thead>
<tr>
<th>Universal Time (approximate)</th>
<th>Celestial Regions Scanned</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200 - 1340</td>
<td>Centaurus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crux</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lupus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Calibration)</td>
<td></td>
</tr>
<tr>
<td>1340 - 1530</td>
<td>Centaurus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lupus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Calibration)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Norma</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scorpius</td>
<td>Solar Flare</td>
</tr>
<tr>
<td>1530 - 1700</td>
<td>(Calibration)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Libra</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ophichus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Calibration)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sagittarius</td>
<td></td>
</tr>
<tr>
<td>1700 - 1850</td>
<td>Ophichus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Calibration)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scorpius</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Centaurus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Norma</td>
<td></td>
</tr>
<tr>
<td>1850 - 1958</td>
<td>Serpens</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ophichus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scorpius</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ara</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 4.6 The scanning trajectories of the telescope axis during the balloon flight on a celestial map. The galactic equator is also shown.
CHAPTER V

DATA ANALYSIS

5.1 OBSERVATION OF DISCRETE X-RAY SOURCES

Due to the scanning program, the concentration of known sources in the scanned celestial regions and the expected low intensity of most of these sources in the energy range of interest, the initial data reduction was performed as follows:

i) First, the totality of continuous PCM data flow was decoded and transformed into a series of 10-second count-rate blocks. Each block contains 22 channel intervals (or energy intervals) grouping different numbers of channels together to insure good statistical properties for every interval. The breakdown of these channel intervals and the approximate counting rate for each at altitude can be found in Figure 4.4 (p.66).

ii) The analog magnetometer data is used to calculate the pointing directions of the telescope every 10 seconds, with due corrections for the position of the balloon and local magnetic variation. Then by careful synchronization, a celestial position was assigned to each 10-second count-rate block and scanning
trajectories are constructed on a celestial map (Fig. 4.6, p.71).

iii) Although the earth's rotation has caused the gradual shift of the scan paths from west to east, the optimized back-and-forth scannings could be combined to accumulate viewing time in a given celestial direction. Thus, in view of the larger acceptance angle (14° FWHM) of the telescope in the direction normal to the circular trajectories, several scan bands with width (maximum separation of scan paths) not more than 10° were formed from closeby and successive scans. Special interest was directed to the two bands that have high trajectory densities and are almost parallel to the galactic plane. Quite a few interesting sources lie within or near the bands. The total length of each scan band was then divided into a number of spatial bins. Depending on location in the sky, the bin size varies from 1 1/2° to 2° and the accumulated viewing time in each bin ranges from less than one minute to more than 6 minutes. All the 10-second count-rate blocks associated with directions inside a spatial bin were summed and averaged. In this manner linear count-rate profiles were obtained for the entire scan band. For the bands along the galactic plane, correspondence between the bins and galactic longitude was established by geometrical projection. Shown in Fig. 5.1 (p.74)
Fig. 5.1 Count-rate profile of scan band A in four channel intervals on which source patterns conforming to the telescope response are superimposed. Derived source positions are shown by arrows, and are designated by Greek letters. The region used for background levels (horizontal broken lines) are indicated.
is a count-rate profile obtained for part of the
galactic plane observed. The effect of summation,
both in channels and viewing time, is obvious:
contribution from discrete sources stand out quite
clearly in at least several energy intervals.*
These count-rate profiles are the basis from which
contributions from sources are isolated and the
corresponding energy spectra derived.

5.1.1 Source-Background Separation

The count-rate due to photons from discrete cosmic
sources, considered the signal in this measurement, is in
most cases a small part of the total count-rate. The rest,
regarded as background, consists of several components:

a) **Cosmic Diffuse Background** - It is not variable
and is isotropic in itself, but is attenuated by the atmos­
phere in the pointing direction of the telescope. Hence its
contribution increases with vertical altitude.

b) **Atmospheric Diffuse Background** - Being anisotro­
pic, in part entering the telescope aperture and in part pen­
etrating the shieldings, its contribution decreases with both
increasing vertical altitude and decreasing geomagnetic lati­
tude, also changes slightly with azimuth due to the east-west
asymmetry of primary cosmic ray flux [cf. Appendix C,(p.182)].

c) **Instrumental Background** - Secondary photons pro­
duced in instrument by interaction with both primary cosmic

---

* For the sake of comparison, the count-rate profile
from a region away from the galactic plane and without known
sources is shown in Figure 5.2 (p. 76).
Fig. 5.2 The count-rate profiles of a portion of scan band C, in which there is no known x-ray source. This is shown to compare with those of scan band A (Fig. 5.1 p.74 ) with the estimated background in scan band A shown here again by horizontal broken lines.
rays and various atmospheric secondaries. It should decrease with increasing vertical altitude and decreasing geomagnetic latitude.

Since vertical altitude, azimuth, and geomagnetic latitude changes continuously during the observation, the background is by no means constant, as is shown in Fig. 4.5 (p.68). For a count-rate profile combined from several scans the background level is actually the average of the possibly different background levels at the respective scans. If N-10-second count-rate blocks are associated with the ith spatial bin in a scan band, the count-rate is given by:

\[ R_i = \frac{1}{N} \sum_{k=1}^{N} R(t_k) \]

\[ = \frac{1}{N} \sum_{k=1}^{N} [S(t_k) + B(t_k)] \]

\[ = \frac{1}{N} \sum_{k=1}^{N} S(t_k) + \frac{1}{N} \sum_{k=1}^{N} B(t_k) \]

\[ = S_i + B_i \]

where

- \( R(t_k) \) = total rate of the kth 10-second block
- \( S(t_k) \) = count-rate contribution from one or more cosmic sources
- \( B(t_k) \) = count-rate contribution from background
- \( t_k \) = time at which the kth 10-second block is centered
- \( S_i \) = averaged source contribution
- \( B_i \) = averaged background contribution
It is clear that while $S_i + B_i$ are not separable, they are independent of each other. If $B_i$ is a good estimate found for $B_i$, then a corresponding estimate of $S_i$, $\bar{S}_i$, could be obtained simply from

$$S_i = R_i - B_i$$

The usual method to find $B_i$ is to use count-rates from celestial direction in which no known sources exist or which exhibit no obvious signs of existence of sources. The accuracy of $\bar{S}_i$ depends on that of $B_i$. Besides counting statistics, error could be introduced by drift of balloon in vertical altitude, geomagnetic latitude, change in telescope azimuth, as well as the incomplete knowledge about discrete sources.

In order to minimize all these possible systematic errors, the $B_i$ were calculated by averaging spatial bins that are in the same scan band, that represent regions void of known sources (in the energy region of interest), and most importantly, where the data shows absence of sources. In both of the interesting scan bands there are such regions formed from several bins (e.g. Fig. 5.1, p. 74). Since the variation of the aforementioned relevant factors during the flight was neither large nor abrupt at any instant (Fig. 4.5, p. 68), the systematic error ($B_i - B_i$) cannot be large. Finally, a linear excess profile $\{\bar{S}_i\}$ was obtained for each scan band.
5.1.2 SOURCE DETERMINATION AND SEPARATION

The determination of source position and intensity depends on the known angular response of the telescope to a parallel photon beam. Contribution from a distant point source will appear, ideally, in a triangular pattern conforming to the angular response of the telescope. But because of the density of x-ray sources in the celestial regions covered by the two scan bands and the limitation in the spatial resolving power of the telescope itself, contributions from sources close to each other in angular distance will not be mutually isolated in the count-rate profile. Their corresponding triangular patterns overlap and hence have to be separated in order to obtain the contributions from the individual sources.

For this purpose, the linear count-rate profiles in the energy intervals between 39 and 65 keV (channels 8-14, the upper two in Fig. 5.1, p. 74) are used as "pilots" in the procedure, since high signal-to-background ratio is expected in this energy range.

Individual triangles (representing "ideal" single source patterns) with the same half width of $6^\circ$ but of different heights are put at different positions in a given count-rate profile to fit the actual count-rate pattern. While the peak position of a triangle indicates the source position, the size of it indicates the apparent strength of the source. More obvious triangular patterns (representing stronger sources such as $\gamma$ and $\sigma$ in Fig. 5.1, p. 74) in the
count-rate profile are fitted first and their corresponding source positions determined. Less obvious patterns (representing weaker sources or close-by sources with similar apparent strengths, such as \(a, \varepsilon\) and \(\eta\)) are fitted with reference to position of known sources and count-rate profiles in lower and higher energy intervals.* The result is illustrated in Fig. 5.1, p. 74. The count-rate contribution from a given source is obtained by summing the rates in bins covered by the triangle representing the source. For any bin in which there is overlapping source patterns, the count-rate will be divided in proportion to the areas under the two triangles and inside the bin. (Details will be provided in a numerical example from the actual data analysis in Appendix D, p.155). All the derived sources have contributions of at least 5 \(\sigma\)'s above background in this energy range (39 - 65 keV) except one (designated \(a\) in Fig. 5.1, p.74 ), which is marginal (2\(\sigma\)).

By assuming the sources and their positions determined in the 39 - 65 keV energy range, the same method is applied to all other energy intervals to determine the count-rate contributions from each of these sources, which is then unfolded, according to the triangular pattern, to arrive at the count-rate as if the source was at the center of the pattern.

*In case that the count-rate pattern suggests the presence of two or more sources in close proximity (in terms of distance projected on the scan paths of the telescope), it might not be practical to separate the contributions.
The final result is a set \( \{ R'_j \} \) for each source representing the differential counting rate distribution (or energy loss spectrum) averaged over the viewing time spent on the source.

5.1.3 Derivation of Primary Spectra

The primary energy spectrum of a given cosmic source as it reaches the top of the atmosphere is of prime interest in this measurement. The relation between this primary energy spectrum and the differential count-rate distribution produced by the telescope-spectrometer involves a series of physical processes that act to transform the former into the latter. They are, in the proper chronological order:

i) Attenuation (absorption and scattering) by the atmosphere before reaching the instrument.

ii) Attenuation by passive instrumental material before reaching detector proper.

iii) Interaction with detector which includes absorption, scattering, and Gaussian broadening.

iv) Electronic signal processing that introduces loss in count-rate.

Therefore, in order to derive the primary energy spectrum, a series of corrections, each associated with a physical process, must be made in the reverse order to the differential count-rate distribution.

a) Deadtime Correction

The major contribution of deadtime comes from the
finite time needed to analyze an accepted event (pulse) and shift the corresponding event word into telemetry. Measurement in the laboratory of the ratio of input and output rates of random pulses provided correction factors as a function of output rates (Fig. 5.2, p. 76). For an output counting rate of 300 counts per second, typical at floating altitude, the correction factor is 1.17, which corresponds to a count-rate loss of about 14%. An additional 2% comes from the 47 sec blanking time for events with energy deposit larger than 1.5 MeV, in the spectrometer as is estimated from the rate monitor data. This raises the total correction factor to 1.19. The same correction factor is applied to every bin in each distribution and it is determined by the average PCM counting rate in the observation period of the corresponding source.

b) **Correction for Effective Exposure**

Because not all the observed sources are in the center of the scan band, the spectrum for each source has to be multiplied by a factor \((\cos^{-1} \theta) \left(1- \tan \frac{\theta}{2} \tan \frac{\theta}{2} \right)\) where \(\theta\) is the half angle in the longitudinal angular response of the telescope and \(\theta\) is the angular distance between the source and the centroidal line of the scan band, which is the average position of all scan paths involved. \(\theta\) ranges from 0° to 8°.

c) **Correction for Detection Efficiency**

As is shown in Fig. 3.4 (p. 45), the interaction efficiency of the NaI(Tl) spectrometer is 100% up to 150 keV and decreases gradually to 55% at 1 MeV; however, the more
Fig. 5.3 Deadtime correction factor as a function of output counting rate of the electronic system.
important photopeak efficiency, which represents efficiency of total energy absorption, is always lower except below 33.2 keV. The loss in photopeak efficiency between 33.2 keV and 150 keV is caused by escape of iodine florescence x-rays produced in photoelectric effect that occur near the crystal surface [Axel (1954); Stein & Lewin (1967)]. Incident photons with energy larger than 33.2 keV could excite iodine atoms which then de-excite by emitting florescence K x-rays with an average energy of 29.2 keV. For the normal incidence at a thick crystal, the probability of escape of these K x-rays can be calculated from

\[ P(E) = 0.367 [1 - r \ln \left( \frac{R+1}{r} \right)] \]

where \( r \) = ratio of the photoelectric absorption coefficients in NaI of the iodine K x-ray (29.2 keV) to that of the incident x-ray (E). The result is the reduction of the photopeak at E by a factor of \( (1-P) \) and the presence of an "escape" peak at energy \( (E - 29.2) \) keV with the ratio of the escape peak to the photopeak being \( \frac{P}{1-P} \). The correction factor for this effect is simply

\[ \frac{1}{1-P(E_i)} \]

for the ith energy interval (Fig. 5.3, p.83). The contribution of the escape peaks are neglected since they are small in every energy bin for rapidly falling energy spectra. Percentage contributions in the case of a power law spectrum of index two is given in Table 511 (p.86) as an example.
Fig. 5.4 Efficiency and absorption correction factors and their product. The absorption correction factor of air is for a typical absorption layer of 2.9 gm/cm² thick.
Table 5.1

<table>
<thead>
<tr>
<th>Energy keV</th>
<th>Detection Efficiency</th>
<th>Input Spectrum $\alpha E^{-2}$</th>
<th>Count-Rate Spectrum Non-Photopeak</th>
<th>Contribution of Iodine Escape Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Photopeak</td>
<td>Non-photopeak</td>
<td>Phoetopeak</td>
<td>Non-Photopeak</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td></td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td></td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>33.3</td>
<td>0.69</td>
<td>0.31</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>40</td>
<td>0.76</td>
<td>0.24</td>
<td>16</td>
<td>13.6</td>
</tr>
<tr>
<td>50</td>
<td>0.82</td>
<td>0.18</td>
<td>11</td>
<td>9.8</td>
</tr>
<tr>
<td>60</td>
<td>0.87</td>
<td>0.13</td>
<td>6.3</td>
<td>5.9</td>
</tr>
<tr>
<td>80</td>
<td>0.93</td>
<td>0.07</td>
<td>4</td>
<td>3.8</td>
</tr>
<tr>
<td>100</td>
<td>0.96</td>
<td>0.04</td>
<td>1</td>
<td>0.97</td>
</tr>
<tr>
<td>200</td>
<td>0.97</td>
<td>0.02</td>
<td></td>
<td>0.31</td>
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<tr>
<td>300</td>
<td>0.77</td>
<td>0.12</td>
<td>0.44</td>
<td>0.15</td>
</tr>
<tr>
<td>400</td>
<td>0.60</td>
<td>0.19</td>
<td>0.25</td>
<td>0.077</td>
</tr>
<tr>
<td>500</td>
<td>0.48</td>
<td>0.23</td>
<td>0.16</td>
<td>0.045</td>
</tr>
<tr>
<td>600</td>
<td>0.41</td>
<td>0.75</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>0.32</td>
<td>0.27</td>
<td>0.063</td>
<td>0.020</td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
<td>0.040</td>
<td></td>
</tr>
</tbody>
</table>
Above 150 keV, the falling off of the photopeak efficiency is due to the gradual dominance of Compton scattering as the interaction process. Yet the photofraction* is above 50% up to almost 1 MeV, because of the fact that multiple Compton scattering in a large crystal enhances the probability of total energy absorption. Therefore, contributions from the Compton continua could be neglected for rapidly falling energy spectra and again here the correction factor for each energy interval is the reciprocal of the photopeak efficiency at the average energy of the interval (Fig. 5.3, p. 83). The values for the photofraction were interpolated from Monte Carlo calculation of Miller et al. (1958). Table 5.1 (p. 74) shows the relative contributions of the various fractions.

d) **Corrects for Passive Attenuation**

The first correction involves the attenuation of the input spectra by the detector window and the gondola top wall, both made of aluminum. The correction factor at energy \( E_i \) is simply

\[
e^{-\mu_{Al}(E_i)d_{Al}}
\]

with the thickness of aluminum \( d_{Al} = 0.24 \text{ g/cm}^2 \) and \( \mu_{Al} \) being the attenuation coefficient of aluminum. It decreases with increasing energy but is independent of energy spectra in question.

* The ratio of photopeak efficiency to total interaction efficiency.
The second correction involves the attenuation of the primary energy spectrum by the residual atmosphere above the instrument. The correction factor has the same form as that for aluminum, i.e.

$$\mu_{\text{air}}(E_i) \cdot d_{\text{air}}$$

but it is different in the determination of both quantities $\mu_{\text{air}}$ and $d_{\text{air}}$. Because of the dominance of Compton scattering as the attenuation process in air above 50 keV the effective attenuation is reduced due to the entry of forwardly scattered photons into the aperture of the telescope. This effect is more important at higher energies since the angular distribution of scattered photons shift from near isotropy to favoring the forward direction and the telescope aperture gradually opens up as energy increases. All values of $\mu(E_i)$ are calculated with due consideration on this effect. The atmospheric depth $d_{\text{air}}$ is time dependent and the value used for each spectrum is the average over the total viewing time spent on the source in question.

5.1.4 Derivation of Spectral Characteristics

The result of the correction procedures is for each source a set of numbers $\{J_j(E_j, \Delta E_j) \pm \sigma_j(E_j, \Delta E_j)\}$, which represents, in the respective energy intervals the most probable mean photonflux values and their associated errors of the measured primary photon spectrum. In order to compare the derived spectra of the observed sources as well as to compare each derived spectrum with characteristic spectra of possible x-ray emission mechanisms (detailed
discussion is provided in Appendix A, p.170), least square curve fitting is performed on each set of spectral points. Both the exponential form

\[ \frac{dJ}{dE} \propto E^{-1} e^{-\frac{E}{kT}} \]

and the power law

\[ \frac{dJ}{dE} \propto E^{-\alpha} \]

are tried in each case. The former represents thermal production in a region of temperature T and the latter points to possibly nonthermal production at the source. The weighted least square method is used to derive the spectral characteristics T and \( \alpha \) and their respective standard deviation. The weighting function is

\[ \frac{1}{\sigma_j^2} \]

5.2 ERROR ANALYSIS

From the initial data reduction to the derivation of primary source spectra, there are various contributions to the error involved in the resulted spectra and hence the spectral parameters.

5.2.1 Random Errors

Random errors stem from the stochastic nature of photon counting by the spectrometer and propagate along every step of the derivation. In a Poisson distribution the usual quantitative measure of random error -- standard
deviation $\sigma$ --- is the square root of the total number of photons counted in a given measurement, which is the product of count-rate $R$ and observation time $T$. In the step of source-background separation, since the estimated source contribution $S = R - B$
where $R$ is the total count-rate and $B$ is the estimated background contribution, the standard deviation $\sigma_S$ is given by

$$\sigma_S = \sqrt{\sigma_R^2 + \sigma_B^2} = \sqrt{\left(\frac{\sqrt{RT_R}}{T_R}\right)^2 + \left(\frac{\sqrt{BT_B}}{T_B}\right)^2}$$

and the fractional standard deviation is given by

$$\frac{\sigma_S}{S} = \frac{\sqrt{\frac{R}{T_R} + \frac{B}{T_B}}}{R - B}$$

5.2.2 Systematic Errors

Systematic errors come from several different origins, all related to the incomplete knowledge of certain pertinent factors during the observation as well as the particular method of subsequent data reduction. They are usually implicit, intermixed and could not be calculated analytically. Examples of systematic errors include changes and uncertainties in (1) telescope pointing directions which affects the summation of both source and background contributions; (2) balloon altitude, which affects the background level and the effective residual atmospheric depth; (3) balloon geomagnetic latitude,
which affects the background level; (4) instrument temperature, which affects the low-energy background level as well as the spectrometer energy calibration.

In order to facilitate due consideration of the contributing factors; the discussion will follow the procedure of data reduction. At each step the magnitude of the systematic errors that come into play will be estimated.

a) **Summation in the scan bands** - Telescope azimuth derived from magnetometer readings are estimated to be accurate within 3° which is small compared to the 6° azimuthal angular FWHM of the telescope. The synchronization between the telescope aspect and spectrometer count-rate has an uncertainty of the same magnitude. Yet the good agreement between the source pattern in the count-rate profile and the telescope response shows that the resulting error are actually smaller throughout.

The gradually shifting scan paths that make up a scan band provide the telescope with changing exposure every time the same source is in view. Any error introduced in the correction of effective exposure to a source from the position of the centroidal line of a scan band depends on the spatial distribution of the scan paths relative to the source position. If the scan paths are all on one side of the source, the systematic error should be limited to that caused by uncertainty in pointing direction. But if the scan trajectories lie on both sides of the source, additional error would be introduced but of no more than 15% since no scan paths are more than 5° away from the centroidal line in the scan bands.
The latter case is true for three sources, GX 331-1, NOR X-1, and GX 340+0.

b) **Source-background separation**

Here the systematic errors determine how close the estimated background level $B$ is to the true background level $B$ (cf. 5.1.1, p.75) and originate from changes in balloon vertical altitude, geomagnetic latitude, telescope azimuth, and instrument temperature during the time span of a scan band. As has been shown in Section 5.1.1 (p.75), the $B$ value in each scan band is averaged from essentially the same individual scans from which the total count-rate $R(=S+B)$ is taken. For either scan band the overall draft in geomagnetic latitude was smaller than 0.05 GV and the total change in altitude did not exceed 0.25 gm/cm$^2$ allowing for the error of pressure measurement. While the maximum possible change in background level due to the former factor will be limited to 1% (judging from known variation in intensity of atmospheric charged particles with geomagnetic latitude), that due to the latter factor will not exceed 4%, according to the count-rate record during the ascent period of the balloon flight. But since changes caused by either factor were distributed over the successive scans, and the flight record shows that the two effects actually acted pretty much against each other (i.e., when the balloon altitude is low, the local geomagnetic cutoff is relatively high, cf. Fig. 4.5, p.68), it could be assumed that the uncertainty caused by the combined effect of these two factors are much smaller and is estimated to be under 0.5%.
This corresponds to typically 10% of the contribution from a strong source and 25% of that from a weak source. The possible variation of the background level with telescope azimuth will cause an error that is roughly proportional to the angular separation between a source and the region in which the background is determined. The maximum angular separation involved is about 45° and hence the maximum systematic error caused by this effect will be limited to 1% as deduced from the measurement between 20 and 150 keV by Agrawal (1972), in which a 4% east-west asymmetry was reported.

Below 40 keV, the background level is also affected by the temperature-dependent photomultiplier noise level, and other systematic effects that have at times caused abnormal fluctuations. In view of the inflight record of both instrumental temperature and average counting rate in the low channels (Fig. 4.5, p. 68), the possible error in background subtraction introduced by temperature changes would be limited to 1%, but that by the latter effect could be larger which is probably responsible for the large scale fluctuations appearing in part of the count-rate profile in the energy range of 29 to 39 keV.

When contributions from two closeby sources were separated, systematic error could be introduced in the process and its magnitude depends on the telescope angular response and signal-to-background in a given energy interval, angular distance between the sources involved and their relative intensities. It should be small in energy intervals below 100 keV, in which source patterns are easier to determine. Above 100 keV,
the uncertainty will increase with energy. But in any energy interval, stronger sources are subjected to less error due to the process.

c) **Energy Calibration**

The gain shift during the total observation time was very small, as is shown in Fig. 4.5, (p. 68) from the time history of the position of the 0.51 MeV gamma line in the background spectrum. Together with the uncertainty in determining the peak position, the error in energy calibration must be smaller than 5% and is hence negligible considering the energy resolution of the spectrometer over the energy range of interest.

Nonlinearity in the response of NaI(Tl) crystal to photons [Birks (1964) Chapter 11] has been incorporated into the calibration curve (Fig. 3.5 p. 47) so that existing error would not be enhanced as in the case of usually assumed straight-line calibration.

d) **Detection Efficiency Correction**

Since the contribution of iodine escape peaks and Compton continua have been neglected, the result of the correction is slight overestimation in photon fluxes at energies lower than 100 keV and higher than 200 keV. The magnitude of the error depends on energy as well as spectral shape. As is shown in Table 5.1 (p. 86), for a power law spectrum of index 2, the overestimation will not exceed 4% for escape peaks and will be less than 1% for Compton continuum.
The Compton contribution from the part of the spectrum above 800 keV is negligibly small. These could be considered as upper limits since all but one of the sources have spectra softer than that of a power law with index 2. For them the actual overestimations are smaller.

e) Atmospheric Absorption Correction

Systematic error is introduced by uncertainty in the effective residual atmospheric thicknesses. The Rosemount pressure gauge has an accuracy of 0.1 mb, i.e. an error of less than 4% for a typical pressure altitude of 3 gm/cm$^2$. The pressure altitude measurement was not frequent enough so that an average over the actual passages of a given source could be calculated. Because of the slow rate of altitude variation during the whole observation (Fig. 4.5, p.68), the effective pressure altitude used for each source should have an error of no more than 5% and in most cases probably smaller than 3%.

As we have seen, the various systematic errors are dependent on energy, spectral shape, time and place, and are therefore different for different sources.

More detailed evaluation is possible but impractical due to the tedious and time-consuming calculation required. Therefore, effort will not be extended to incorporate them into the final form of the source spectra. Nevertheless, the estimated magnitude of systematic errors from the most important factors will be given for each source in Table 7.1 (p.141).
CHAPTER VI

RESULTS AND DISCUSSIONS

6.1 Hard X-Ray Survey of the Galactic Plane

The first concrete and interesting result of the data analysis is the hard x-ray profile of the galactic plane from $l^{II} = 290^\circ$ through the galactic center ($l^{II} = 360^\circ$ or $0^\circ$) to $l^{II} = 20^\circ$ obtained from scan bands A and B (Fig. 6.1, p. 97). It is believed that there is no appreciable (diffuse) hard x-ray emission from the galactic disk except that from discrete sources [Silk (1973)] and data from scan band C which crosses the galactic plane at $l^{II} \approx 15^\circ$ does not show otherwise (Fig. 6.1 p.97). With scan bands A and B combined, the linear count-rate profile projected over galactic longitudes, as shown in Fig. 6.2(b), (p.99), reveals clearly the presence of discrete sources in different energy intervals.

Between 39 and 50 keV, there are three "peaks" that are more than 15 $\sigma$'s, three more than 8 $\sigma$'s above the estimated background all of which could be considered unambiguous sources. There are four "peaks" that are more than 5 $\sigma$ but these overlap with larger "peaks". One is 2 $\sigma$'s above background, yet isolated from other sources. When compared with a similar survey in soft x-rays [Seward et al. (1972)] Fig. 6.2(a), (p.99), most of the outstanding sources in both cases match well in position. General distribution of sources is also similar: concentrations in Crux-Centaurus ($l^{II} = 290^\circ$-
Fig. 6.1 X-ray sources in the part of the sky scanned during the balloon flight are shown in galactic coordinates. Circles (open or filled) indicate sources in the third UHURU catalog [Giacconi et al. (1973)], with different sizes showing their relative intensities in 2-6 keV. Squares (open or filled) indicate rocket sources not matched with UHURU sources. Filled circles or squares indicate sources that have been observed from balloon altitudes. Centroidal lines of the scan bands are shown with peak position marked for the observed sources. Also shown is the size of the telescope aperture in terms of FWHM in angular response at low energies.
Fig. 6.2 The x-ray profiles of the galactic plane between \( \lambda \equiv 290^\circ \) and \( 20^\circ \) at different energy intervals. Part (a) shows the soft x-ray results of Seward et al. (1972). Part (b) shows the result of the present work in 5 consecutive energy intervals combined from scan bands A and B. The eleven resolved sources are designated by the Greek alphabets \( \alpha \) to \( \lambda \). Vertical broken lines indicate source positions while horizontal broken lines show the estimated background levels.
Figure 6.2

COUNTS sec⁻¹

GALACTIC LONGITUDE

0° 90° 180° 270° 360° 315° 225° 135° 45° 0°

100 200 300 400 500 600 700 800

2-20 keV

GX 17+2
GX 9+1
GX 5+1
GX 3+1
GX 349+2
GX 340+0
CIR X-1
GX 304-1
CEN X-5
CEN X-3

UNH Survey May 1970
LLL Survey May 871
100

308°), Lupus-Norma (\(\ell_{II} = 318°-338°\)), Ara-Scorpius (\(\ell_{II} = 338°-355°\)), and Saggitarius (Galactic Center region), with a void between \(\ell_{II} = 308°\) and \(\ell_{II} = 318°\) which was used in background determination.

Because of the limited spatial resolving power of the hard x-ray telescope, not all the sources are well separated, especially in well populated areas such as the Galactic Center region or the Lupus-Norma neighborhood. But by studying known source positions from existing catalogs [Giacconi et al. (1973); Seward et al. (1970)] and other published observational reports, a total of eleven sources could be derived from the data with various degrees of certainty [designated by the first Greek letters in Fig. 6.2(b)]. They are listed together with identifications in Table 6.1,(p.101). Also listed is their intensities in terms of number of standard deviations above background between 39 and 50 keV. While for several "peaks" highly probably one-to-one correspondence with known sources could be established, uncertainty cannot be avoided in the identification of sources that are either weak or crowded together or both. In addition, the possibility cannot be ruled out that a new source which has never been reported was observed, or a source changed its intensity relative to that given in the reports since many of them are known to be variable. According to the distribution of known sources within 10° of the galactic equator, the long span can be conveniently divided into four regions (Fig.6.1,(p.97). 

a) The Crux-Centaurus region (\(\ell_{II} = 290°-310°\)). This region has been noted for its variable sources, such as the first
Table 6.1

<table>
<thead>
<tr>
<th>Source Observed</th>
<th>Most Probable Identification</th>
<th>Other Possible Contributing Known Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[Rocket/Balloon Source]</td>
<td>[UHURU source]</td>
</tr>
<tr>
<td>α (2)*</td>
<td>CEN X-5</td>
<td>3U1145-61 (72/5)**</td>
</tr>
<tr>
<td>β (4)</td>
<td>GX 301-2</td>
<td>3U1223-62 (32/3)</td>
</tr>
<tr>
<td>γ (25)</td>
<td>GX 304-1</td>
<td>3U1258-61 (47/5)</td>
</tr>
<tr>
<td>δ (6)</td>
<td>CIR X-1</td>
<td>3U1516-56 (720/20)</td>
</tr>
<tr>
<td>ε (4.5)</td>
<td>NOR X-2</td>
<td>eU1538-52 (11)</td>
</tr>
<tr>
<td>§ (12.5)</td>
<td>GX 331-1</td>
<td>3U1543-47 (2000/100)</td>
</tr>
<tr>
<td>η (8.7)</td>
<td>NOR X-1</td>
<td>3U1630-47 (150/3)</td>
</tr>
<tr>
<td>θ (18.7)</td>
<td>GX340 + 0</td>
<td>3U1642-45 (381/3)</td>
</tr>
<tr>
<td>τ (8.3)</td>
<td>GX349 + 2</td>
<td>3U1702-36 (715/2)</td>
</tr>
<tr>
<td>κ (12)</td>
<td>GX357 + 2.5</td>
<td></td>
</tr>
<tr>
<td>λ (19.7)</td>
<td>[GX 1 + 4]</td>
<td>3U1728-24 (60)</td>
</tr>
<tr>
<td></td>
<td>[GX 3 + 1]</td>
<td>3U1744-26 (460/3)</td>
</tr>
<tr>
<td></td>
<td>[GX 5-1]</td>
<td>3U1758-25 (1127/2)</td>
</tr>
</tbody>
</table>

* Observed intensity in terms of number of standard deviations above the estimated background in the energy range of 39-50 keV.

**(Maximum count-rate/variability factor) as given in 3U catalog [Giacconi et al. (1973)].
transient source CEN X-2 which has now disappeared (of §1.2.1, p.20) and the first source to be established as an eclipsing binary, CEN X-3 [Schreier et al. (1972)].

Among a total of eight low-energy sources in this region, three of the four brighter ones, CEN X-5, GX 301-2, and GX 304-1 could be identified with the rather well-resolved "peaks", $\alpha$, $\beta$, and $\gamma$ in our observation. The latter two have been known to have highly variable hard x-ray components [Ricker et al. (1973)]. Yet the famous CEN X-3, though the brightest in soft x-ray in this region, was not observed.

b) The Lupus-Norma region ($l^\text{II} \approx 318^\circ - 338^\circ$). This region has been surveyed many times by rocket experiments during the last ten years [Friedman et al. (1967)]. Yet there are still discrepancies in several source positions in the different reports. For instance, NOR X-1 and NOR X-2 have repeatedly been seen in most rocket observations but do not coincide in position with any of the 8 UHURU sources in this area. Only one rocket observation [Cruddace et al. (1972)] reported source positions more agreeable to those in the UHURU catalog. This has caused difficulties in source identification in this region. Our data showed four relatively weak sources, $\delta$ to $\eta$ which could best be identified with CIR X-1, NOR X-2, GX 331-1 and NOR X-1. CIR X-1 was recently suspected to be similar to CYG X-1 [Jones et al. (1974)]—the much discussed "black hole" candidate. GX 331-1 was independently observed by both satellite and balloon experiments six months after our measurement [Ricker et al. (1974)].

c) The Ara-Scorpius Region ($l^\text{II} \approx 338^\circ - 358^\circ$). This region
is part of the crowded regions near the galactic center with a total of at least 13 known sources at low energies. Despite the fact that it has the highest source density in any region in the sky, two very bright sources, though variable in intensity, always stood out above others in every survey for photon energies as high as 30 keV [Seward et al. (1972); Peterson (1973)] and have also been observed from balloon altitudes [Davison et al. (1971); Mahoney (1973)]. Thus, they are readily identified with the two peaks θ and ν, which appear in both scan bands A and B. There might be a non-separable contribution from other sources in the field of view of the telescope, such as 3U1700-37, 3U1705-44, and 3U1746-37 (GX 354-5), since both of them have possibly been observed from balloon altitudes [Ricker et al. (1974); McClintock et al. (1972); Davison et al. (1971)]. The well-resolved peak κ points to a small region where there seems to be void of low energy sources except for one, GX 357 + 2.5, which was observed only once in 1969 [Cruddance et al. (1972)].

d) The Sagittarius - Serpens region (l^II = 358° - 20°). This region includes the galactic center near which several strong sources seem to arrange themselves in a more orderly manner with their positions as well as intensities being consistent in both rocket and satellite surveys. Most of the hard x-ray measurements have observed localized emission from directions near the galactic center but failed to resolve the possible contributing sources and were uncertain
or inconsistent when attributing the emission to a single source [Davison et al. (1971); Mahoney (1973); Johnson (19720)]. Recent balloon measurements by one group [Ricker et al. (1973a); Ricker, et al. (1974)] did resolve the three sources—GX 1+4, GX 3+1, and GX 5-1 within 6° of the galactic center and found all three to have substantial hard x-ray emission. The rather broad peak λ in our data is probably due to the combined emission from these three sources. No appreciable emission was observed from the sources GX 9+9, GX 9+1, GX 13+1, and GX 17+2, despite their high brightness in soft x-rays.

6.2 Spectra of Individual Sources. Spectra derived from the data will be discussed according to the most probable identifications and in the order of increasing galactic longitude.

i) CEN X-5 (3U1145-61) The source was first and only once observed by a rocket measurement in 1970 [Hill et al. (1972)] and agrees well in position with the variable source 3U1145-61. No hard x-ray measurement has ever been previously reported for this source. Our data, averaged over eleven scans in a time span of 100 minutes, showed marginal flux from a very steep spectrum between 22 keV and 50 keV (Fig. 6.3, p.106). A best-fit power law of index α = 4.3 ± 2.2 is not compatible with the rocket and UHURU results. The rocket data show a best-fit power law spectrum of index 2.5± 0.4 between 1 and 20 keV; but if the lower limit in spectral index is taken, the lower energy spectrum would intercept our hard x-ray spectrum around 20 keV, thus forming a continuous
Fig. 6.3 Spectrum of CEN X-5. Error bars and upper limits shown are of 1σ. ILL soft x-ray result is taken from Hill et al. (1972). Satellite data on CEN X-3 [Baity et al. (1974)] is shown for comparison. Best-fit spectra are represented by solid and broken lines with their corresponding spectral characteristics indicated.
Figure 6.3

CEN X-5
(3U1145-61)

LLL (May 13, 1970)
UNH (Nov. 22, 1971)
(CEN X-3)
UCSD-OSO7

PHOTON FLUX (Photons/cm^2-sec-keV)

ENERGY (keV)

$E^{-2.1}$
$E^{-4.3}$
$E^{-1}e^{-E/10}$ keV
spectrum with a rather large "break" ($\Delta \alpha \approx 1.3$) at an energy around 20 keV. On the other hand, a best-fit exponential spectrum requires $kT = (10 \pm 7$ keV), which does not quite agree with the $kT \sim 3$ keV also reported in the rocket data. Both models have similar likelihoods, as judged from the confidence levels in the chi-square fitting. But the exponential spectrum seems to be better when the UHURU intensity and the upper limits in fluxes above 50 keV are also considered. Since no two existing measurements were made simultaneously and the source has a variability factor of five in 2-6 keV, discrepancies in results might not be unreasonable. Although no x-ray periodicity has been observed for CEN X-5, the possible optical candidate proposed for 3U1145-61, WRA 977 [Vidal (1973)] is a star with intensity variation suggestive of a 13.5 day periodicity [Mauder (1974)]. Distance estimation from soft x-ray data has put CEN X-5 in the same galactic neighborhood of CEN X-3, a well-established binary system, and the two sources should have similar x-ray luminosities [Seward et al. (1972)]. In the limited existing spectral data of the two sources [Baity et al. (1974)], there do not seem to be striking differences between the two (Fig. 6.3, p.106) and therefore it is entirely possible that CEN X-5 is a binary system similar to CEN X-3, yet with the orbital plane in an orientation unfavorable for any obvious eclipsing phenomena to be observed in x-rays.

ii) GX 301-2 (3U1223-62) This source in Crux was first discovered from a balloon observation in April, 1969,
but was not seen by the same telescope only a month earlier [Lewin et al. (1971)]. Its intensity varied by a factor of three within an hour. A later observation in October, 1970, unveiled even higher variability in the same energy range, 18-36 keV [McClintock et al. (1971)]. Several flares with rise and decay times of a few minutes were recorded. A change in flux of about a factor of five in 2.5 minutes was observed. In soft x-rays the UHURU data showed a rather flat spectrum and a variability of three in the energy range 2-6 keV, but the maximum intensity is two orders of magnitude below the extrapolated value from the hard x-ray spectrum measured [Ricker et al. (1973a)].

Our data show positive flux from GX 301-2 between 17 to 50 keV, which is averaged over 13 scans within a time span of 90 minutes. The derived photon spectrum (Fig. 6.4, p.109) could be best-fitted either with a power law index $\alpha = 5.52 \pm 0.35$ or an exponential function (for hot this plasma) with $kT = (6.1 \pm 4.8$ keV). But the latter agrees better with the upper limits in fluxes above 50 keV. Our results seem to agree reasonably well with that of Ricker et al. (1973a). Fig. 6.5 (a), (p.110) shows the different hard x-ray (18-36 keV) intensities of GX 301-2 observed by several experiments, including the present work, during a four year time span.

iii) GX 304-1 (3U1258-61) This source in Centaurus, discovered in October, 1967, in a balloon measurement, was first wrongly identified with the transient source CEN X-2 [Lewin et al. (1968)] and later found to be a separate
Fig. 6.4 Spectrum of GX 301-2. Error bars and upper limits shown are of 1σ. MIT data is taken from Ricker et al. (1973a). Best-fit spectra are represented by solid and broken lines with their corresponding spectral characteristics indicated.
Fig. 6.5 The intensity of (a) GX 301-2 and (b) 304-1 in the energy range between 18 and 36 keV at different times from 1967 to 1972. MIT data are taken from Ricker et al. (1973a) and Ricker et al. (1974). Best-fit spectra are represented by solid and broken lines with their corresponding spectral characteristics indicated.
variable source [Francey (1971)]. The first indication of its variability was that its intensity decreased and its spectrum above 20 keV changed between two observations that were separated by only nine days. Meanwhile an x-ray telescope onboard the satellite OSO III has provided an almost continuous record of x-ray emission (7-113 keV) from the neighborhood of GX 304-1 from October, 1967, to June, 1968, [Schwartz et al. (1972)]. It showed flaring activities on top of a rather constant "quiet time" flux. While the individual flares added excesses below 40 keV, the "quiet time" spectrum agreed quite well with that from the balloon data up to about 100 keV, with similar but changeable flattening tendency at the high end which did not correlate with changes below 40 keV.

A most interesting development was the possible gradual disappearance of the hard x-ray portion of the spectrum from this source, as reported by subsequent balloon observations in 1968 [Davison et al. (1971)] and in 1969 [Lewin et al. (1970)], followed by its reappearance in 1970 with intensity smaller and spectrum softer than in 1967 [McClintock et al. (1971); Ricker et al. (1973a)]. In our data this source turned out to be the brightest of the eleven we observed; positive flux was recorded between 17 and 210 keV when averaged over 14 scans with a time span of 90 minutes. The derived photon spectrum (Fig. 6.6, p.112) could be best-fitted with an exponential form with $kT = (22 \pm 1.2$ keV) or a power law with spectral index changed at $\sim 45$ keV.
Fig. 6.6 Spectrum of GX 304-1. Error bars and upper limits shown are of 1σ. MIT data is taken from Lewin et al. (1968). OSO III data is taken from Schwartz et al. (1972). Best-fit spectra are represented by solid and broken lines with their corresponding spectral characteristics indicated.
\( \alpha = 1.8 \pm 0.2 \) for 17 to 45 keV, and
\( \alpha = 4.5 \pm 0.2 \) above 45 keV.

When compared with the OSO III measurement in 1967, our data below 45 keV is compatible with that of a flaring or "high-state" spectrum. Below 20 keV, the MIT-OSO 7 observation of the source 2U1258-61 over 24 days has recorded a four-day "high-state" [Ricker et al. (1973a)], the spectrum of which is quite compatible with the exponential fit of our data, although the UHURU data point in 2-6 keV is about an order of magnitude lower. Above 45 keV, our data does not agree with either of the two previous MIT measurements, which is probably another indication of the complex variability of this source. Shown in Fig. 6.5 (b), (p.110) is the flux from GX 304-1 in 18-36 keV as measured at different times by different experiments. The possible appearance of a long-term variation of the intensity of the source could very well be the result of complex short-term variability and sporadic short-duration observations. Considering the complexity in its temporal and spectral variation, GX 304-1 should be considered as one of the most interesting sources, although no optical or radio identification has yet been suggested. As a first step to understand further about this source, simultaneous soft and hard x-ray observation would be very useful.

iv) CIR X-1 (3U1516-56) This source in Circinus was first observed during a rocker flight in 1969 and found to be pulsating in soft-x-rays, with a period of
0.685 sec. [Margon et al. (1971)]. Its photon spectrum could be best-fitted by blackbody or bremsstrahlung models, both with temperature of the order of 10^7 °K and showed heavy absorption below 2 keV, an indication that the source might be distant [Seward et al. (1972)]. Identified with the source 3U1516-56 (which was once confused with a nearby rocket source LUP X-1), the UHURU data showed irregular variability in CIR X-1 of a factor of 20 on time scales as short as 0.1 second. There did not seem to be any clearly stable period present, although various quasi-stable periods might be found occasionally in pulse trains of lengths of tens of seconds [Schrier et al. (1971); Forman et al. (1973); Spada et al. (1974)]. In addition, the UHURU observations suggested the presence of a 12.288 day occultation cycle which is indicative of possible binary nature of the source [Jones et al. (1974)], although there are conflicting reports from the OSO-7 satellite [Canizares et al. (1974)]. Higher-energy observations (7-57 keV) by the OSO-7 satellite [Baity et al. (1974)] have shown no periodicity but did show high variability in both intensity and spectral shape with a photon spectral index \( \alpha \) varying from \((1.1 \pm 0.1)\) to \((3.0 \pm 0.5)\) within 110 days. All this evidence points to the similarity between CIR X-1 and CYG X-1, a binary system strongly suspected to involve a collapsar (i.e. a "black hole", cf. Section 1.2.1, p.14). Furthermore, a possible optical candidate for CIR X-1 has been suggested -- a peculiar red carbon star with characteristics similar to other stars that might be in binary
systems [Wickramasinghe et al. (1974)].

Our data has produced a photon spectrum between 30 and 500 keV (Fig. 6.7, p.116) averaged over 18 scans within a time span of 170 minutes. The best-fit spectrum is a power law with spectral index $\alpha = 2.4 \pm 0.3$ between 30 and 210 keV (or with less confidence, $\alpha = 1.7 \pm 0.2$ between 30 and 500 keV), which is in good agreement with the "high state" spectrum in 7-57 keV reported by Baity et al. (1974). In fact, CIR X-1 has the hardest spectrum among those of the eleven sources we measured, which seems to add to the similarity between CIR X-1 and CYG X-1. The hard x-ray photon spectrum of CYG X-1, though changeable and exhibiting "high" and "low" states [Matheson (1971)], is quite consistent with a power law spectrum of spectral index $\sim 2$ as measured by many experiments [e.g. Haymes and Harnden (1970); Webber and Reinert (1970; Mahoney (1973)]. Shakura and Sunyaev (1973) have discussed and calculated different possible radiation spectra from the accretion disk in a binary system involving a black hole. In one case, the emerged high-energy photon spectrum actually has the form of a power law with index 2 between 15 and 100 keV; however, beyond 100 keV, the spectrum begins to fall off. The spectrum of CYG X-1 does show evidence of falling off in the hundred keV region [Mahoney (1973)]. But in our data for CIR X-1, it is not obvious whether a similar fall-off is present.

v) NOR X-2 This source has been on the list of soft x-ray sources in the Norma-Lupus region for a long time
Fig. 6.7 Spectrum of CIR X-1. Error bars and upper limits are of 1σ. OSO-7 data is taken from Baity et al. (1974). Best-fit spectra are represented by solid and broken lines with their corresponding spectral characteristics indicated.
[Friedman et al. (1967); Oda and Matsuoka, 1971]). While it is not a strong source and is probably not highly variable, neither are the two UHURU sources (3U1538-52 and 3U1556-60) closest to its position. There are two previous hard x-ray observations on this source [Lewin et al. (1968a); Davison et al. (1971)] and positive measurements exist only up to about 40 keV. Also because of the density of sources in this region and the variability of some neighboring sources, such as CIR X-1 and LUP X-1, some of the data attributed to NOR X-2 could in part or in total have come from a nearby source or sources. But since we have separated CIR X-1 from this source in our data we are able to discuss this source independently while keeping in mind the possible confusion in some previous measurements as well as the uncertainty in our identification.

Our data showed positive flux from this source in the energy range of 22 to 315 keV. The derived spectrum (Fig. 6.8, p.119) averaged over 23 scans within a time span of 220 minutes, can be best-fitted by a power law of spectral index $\alpha = 2.83 \pm 0.24$, although the spectrum is actually softer below 100 keV and is consistent with an exponential spectrum with $kT = (12 \pm 2$ keV). In this light the indication of flattening above 100 keV points to possible similarity between this source and the well observed SCO X-1 (cf. Fig. 1.4, p.15). In a model to interpret the measured spectrum of SCO X-1, Zeldovich and Shakura (1969) have discussed the x-ray emission accompanying the spherical
Fig. 6.8 Spectrum of NOR X-2. Error bars and upper limits shown are of 1σ. The MIT data is taken from Lewin et al. (1968). Soft x-ray data is taken from Cooke and Pounds (1970). Best-fit spectra are represented by solid and broken lines with their corresponding spectral characteristics indicated.
Figure 6.8
accretion of gas by a central neutron star. The accreting gas by differential heating would generate in the atmosphere of the neutron star a hot outer layer, the temperature of which could be an order of magnitude higher than the inner layer. While soft thermal x-rays are emitted from the cooler inner layer, hard x-rays are produced in the hot, outer layer. It is this enhancement in the fluxes between 10 - 100 keV that causes the appearance of "flattening" in the resultant spectrum.

vi) **GX 331-1** The existence of this source was not known until a balloon observation first detected it on April 25, 1972, (six months after our flight); and it was later confirmed in the soft x-ray data from the OSO-7 satellite [Ricker et al. (1974)]. Without this knowledge, we have in the preliminary report of our results [Guo et al. (1973)] tentatively identified the observed source with the transient source 3U1543-47, which was the only bright source inside the aperture of the telescope but was 6° away from the centroidal line of scan band A. But since the reported position of GX 331-1 lies almost on the centroidal line and the reported intensity in 20-42 keV is in excellent agreement with our data, it is very probable that it is the source we observed although we do not have soft x-ray information on the source on or near November 22, 1971.

The transient source 3U1543-47 first appeared on July 26, 1971, reached maximum on July 31 and gradually declined in brightness thereafter [Belian et al. (1973)]. On
November 22, its intensity at low energies was approximately 1/3 of that at maximum, which made it almost as bright as GX 5-1 (cf. Fig. 6.2, p.99) and the brightest in the Norma-Lupus region in soft x-rays [Matilsky et al. (1972)]. The fact that its spectrum seems to have remained soft, despite sporadic fluctuations, could probably explain the failure of attempts to detect hard x-rays from 3U1543-47 [Pizzichini et al. (1974); Ricker et al. (1973b)]. Taking the intensity and spectral index measured by the UHURU satellite on November 25 and extrapolating to the hard x-ray region, the intensity of 3U1543-47 would be at least an order of magnitude below our derived spectrum above 20 keV as shown in Fig. 6.9, (p.122). We could thus conclude that the contribution from 3U1543-47 was small enough to be neglected and the spectrum could be safely attributed to GX 331-1.

Our data showed positive flux from GX 331-1 between 22 and 315 keV, (Fig. 6.9, p.122). The derived spectrum, averaged over 26 scans within a time span of 160 minutes, turned out to be too complex to be fitted by any simple function. Yet it might be approximated by a power law spectrum of changing spectral index as follows:

\[
\alpha = \begin{cases} 
3.0 \pm 0.3 & 29 - 95 \text{ keV} \\
0.8 \pm 0.5 & 95 - 210 \text{ keV} \\
\geq 5.3 & > 210 \text{ keV}
\end{cases}
\]

In fact, between 22 and 95 keV, an exponential spectrum with \( kT = (25 \pm 3 \text{ keV}) \) gives a better fit.

It is difficult to consider the implication of this
Fig. 6.9 Spectrum of GX 331-1. Error bars and upper limits shown are 1σ. The MIT data is taken from Ricker et al. (1974). Best-fit spectra are represented by solid and broken lines with their corresponding spectral characteristics indicated.
interesting spectrum without any knowledge of the soft x-ray intensity. The absence of any UHURU source at the position of GX 331-1 probably means that this source has an intensity in 2-6 keV much lower than that of 3U1543-47 at that time. If this is so there would be a discrepancy between soft and hard x-ray portions of the spectrum of GX 331-1 that could only be explained by a turn over of the spectrum at an energy near 10 keV, a situation already suggested for the source GX 301-2 [Ricker et al. (1973a)].

vii) NOR X-1 (3U1630-47 and/or 3U1624-49) This is also a relatively weak source in Norma that has been known to exist for some time from rocket observations [Friedman et al. (1967)]. Although no variability in this source has been reported, both UHURU sources (3U1630-47 and 3U1624-49) that are closest to the rocket position and might be identified with it are variable. One rocket measurement did report a source position consistent with that of 3U1630-47 [Cruddance et al. (1972)]. Another UHURU source that lies in the field of view of the telescope is 3U1658-48 (GX 339-4) has been found to be highly variable and exhibit "on" and "off" states [Markert et al. (1973)]. But the same report showed that the source was in a steady "off" state on November 22, 1971. Although the UHURU intensity of 3U1658-48 (maximum) is higher than that of 3U1630-47 and 3U1624-49 together, OSO-7 data showed that the former had a spectrum much softer than that of NOR X-1 and the "off" state is at least 60 times less intense than the "on" state. Therefore, we could safely
assume there was no significant contribution from 3U1658-48 in our data.

Our data showed positive flux from NOR X-1 between 22 and 210 keV. The derived photon spectrum averaged over 24 scans within a time span of 160 minutes (Fig. 6.10, p.126) is consistent with a single power law with spectral index $\alpha = 3.5 \pm 0.3$, the extrapolation of which to lower energies does not agree with available soft x-ray data. An exponential spectrum with $kT = (15 \pm 2$ keV) will lessen this discrepancy at low energies but does fit our data as well as the power law. Only one previous hard x-ray measurement was possibly attributed to this source [Davison et al. (1971)] and the reported spectral points are shown together with our results. The agreement is reasonably good.

viii) GX 340 + 0 (3U1642-45) This is a strong soft x-ray source in Ara which was observed as early as 1965 [Friedman et al. (1967)] and remained outstanding in several surveys of this region [MacGregor et al. (1969); Hill et al. (1972); Peterson (1973)]. Although the UHURU data showed that it has a variability factor of three in 2-6 keV, no periodicity has been found at low energies [Rappaport et al. (1971)]. There was a suggestion that it is a highly compact blackbody source, possibly a neutron star with a radius of $8 \pm 4$ km at a distance of $\sim 4$ kpc from the earth [Margon et al. (1971)], but another measurement has implied a distance of 13 kpc for the source, thus making it the most distant and the most luminous ($6.6 \times 10^{38}$ erg/sec) x-ray emitter.
Fig. 6.10 Spectrum of NOR X-1. Error bars and upper limits shown are of 1σ. University of Adelaide data is taken from Davison et al. (1971). Soft x-ray data is taken from Cooke and Pounds (1970). Best-fit spectra are represented by solid and broken lines with their corresponding spectral characteristics indicated.
Figure 6.10

NOR X-1

-log_{10}(\text{PHOTON FLUX}) (\text{cm}^2 \cdot \text{sec} \cdot \text{keV}^{-1})

-3.5

$E^{-1}e^{-E/15\text{keV}}$

\(\bigcirc\) U Leicester June 1968

\(\dagger\) U Adelaide Feb. 1968

\(\blacklozenge\) UNH Nov. 1971
known in our galaxy [Seward et al. (1972)]. It is perhaps remarkable that the latter distance should be the same as the pulsar PSR 1641-45, which was suggested to be possibly associated with GX 340 + 0 by position coincidence only [Ables et al. (1973)]. Two hard x-ray measurements of this source up to about 60 keV have been reported previously [Lewin et al. (1969); Davidson et al. (1971)].

In our data, this source appeared as a strong source with positive flux observed from 39 to 500 keV. The photon spectrum, obtained by averaging over 11 scans in a time span of 60 minutes, is shown in Fig. 6.11, (p.129) together with available rocket, satellite and other balloon data. Our spectral points in a greatly expanded energy range, seem compatible with earlier hard x-ray measurements, although they are not consistent with any simple spectral function, a situation quite similar to that of NOR X-2, (p.119). A best-fit power law with index $\alpha = 3.5 \pm 0.2$ will cause intensity discrepancy at the low energies, and the spectrum between 39 and 125 keV is actually softer. A best-fit exponential spectrum with $kT = 18.7$ keV below 100 keV will lessen the intensity discrepancy between soft and hard x-ray measurements but at the same time implies an "excess" of hard x-rays above 100 keV over the extrapolated exponential spectrum.

ix) GX 349 + 2 (3U1702-36) This source in Scorpius has long been known to be a strong and variable source in soft x-rays [Gorenstein et al. (1967); Fisher et al. (1967);
Fig. 6.11 Spectrum of GX 340+0. Error bars and upper limits shown are of 1σ. The MIT data is taken from Lewin et al. (1969). The UCB data is taken from Crudace et al. (1972). Best-fit spectra are represented by solid and broken lines with their corresponding spectral characteristics indicated.
Figure 6.11

PHOTON FLUX (Photons/cm²-sec-keV)

ENERGY (keV)

GX 340+0
(3U1642-45)

UHURU
UCB (June 14, 1969)
MIT (Mar 20, 1969)
UNH (Nov 22, 1971)
Cruddance et al. (1972). UHURU data has shown that it is one of the brightest soft x-ray sources on the galactic plane and has a variability factor of 2 in 2-6 keV [Giacconi et al. (1973)]. No periodicity has been found at lower energies [Rappaport et al. (1971)]. While the soft x-ray spectrum could not be satisfactorily fitted with any simple function, which is unusual [Cruddace et al. (1972)], the turn-over near 1.5 keV could imply that the source is distant [Seward et al. (1972)]. Detailed spectral information as well as temporal variation in hard x-rays up to 160 keV was provided by a balloon measurement in 1969 [Mahoney (1973)]. Flaring activity with intensity changes by a factor of two over periods of the order of 10 minutes was observed, yet spectra of various intensities were all consistent with a power law of spectral index $\alpha = 2.9$.

In our data, GX 349 + 2 appeared outstandingly in both scan band A and B, with the two observation periods separated by approximately 4 1/2 hours. Spectral distribution between 39 keV and 315 keV was obtained for both periods (Fig. 6.12, p.132) and no significant difference seems to be present. Both cases were consistent with a best-fit power spectrum of index $\alpha = 3.4 \pm 0.4$, which is quite compatible with that reported by Mahoney (1973).

x) GX 357 + 2.5 This source was possibly observed only once in soft x-rays by a rocket flight in 1969 [Cruddace et al. (1972)], and there is no other known non-transient source within a radius of three degrees from this source,
Fig. 6.12 Spectrum of GX 349+2. Error bar and upper limits shown are of 1σ. UCB data is taken from Mahoney (1973). Soft x-ray data are taken from Fisher et al. (1967) and MacGregor et al. (1969). Best-fit spectra are represented by solid and broken lines with their corresponding spectral characteristics indicated.
Figure 6.12
nor any in the field of view of the telescope. The short-lived transient source GX 359 + 2 was close in position (Fig. 6.1, p.97), but was reported as undetectable by the UHURU satellite after March, 1971, [Kellogg et al. (1971)]. Although a subsequent balloon experiment that surveyed this part of the sky in April, 1972, did not report any source in this position [Ricker et al. (1973b, 1974)], the existence of large-scale yet irregular hard x-ray variability in sources like GX 301-2 and GX 304-1 [Ricker et al. (1973a)] shows the possibility that GX 357 + 2.5 is a highly variable source similar to GX 301-2 and GX 304-1 (cf. Fig. 6.5, p.110).

The spectrum derived from our data is shown in Fig. 6.13, (p.135) together with the low energy data of GX 357 + 2.5. The spectral points between 39 and 125 keV were obtained by averaging 7 scans in a time span of 50 minutes. A best-fit power law of index $3.6 \pm 0.3$ will extrapolate to low energy intensities much above those reported for GX 357 + 2.5, while a best-fit exponential spectrum with $kT = (24 \pm 3$ keV) agrees reasonably well with the low energy points. But the temperature implied, $2.8 \times 10^8 \, ^\circ$K, is much higher than the $5.6 \times 10^7 \, ^\circ$K derived from the low energy data [Cruddance et al. (1972)].

xi) Galactic Center Region The three hard x-ray sources GX 1 + 4 (3U1728-24), GX 3 + 1 (3U1744-26), GX 5-1 (3U1758-25), each situated no more than six degrees away from the galactic center, are close together from the perspective of our telescope's aperture and it is beyond the
Fig. 6.13  Spectrum of GX 357+2.5. Error bars and upper limits shown are of 1σ. UCB data is taken from Cruddace et al. (1972). Best-fit spectra are represented by solid and broken lines with their corresponding spectral characteristics indicated.
Figure 6.13
spatial resolving power of our instrument to separate them. In soft x-rays, GX 5-1 is the brightest non-transient source on the galactic plane with its intensity being about 2 1/2 times that of GX 3 + 1, and more than ten times that of GX 1 + 4, which is the only nonvariable one of the three [Giaconi et al. (1973); Seward et al. (1972)]. But in hard x-rays, GX 1 + 4 has been found to be not only brighter than GX 5-1 and GX 3+1, but also variable [Ricker et al. (1973a); Ricker et al. (1974)]. Our data shows positive flux from this region from 17 to 125 keV. Averaged over nine scans in a time span of 50 minutes, the derived spectrum seems to be softer but higher in intensity than previously reported hard x-ray spectra of any of the three individual sources. It is interesting to note that by summing the spectra of the three sources where they are resolved as reported by Ricker et al. (1973a) and Ricker et al. (1974), the resultant data points between 18 and 65 keV are quite compatible with our measurement. This is consistent with the idea that we have measured the combined emission from all three. As shown in Fig. 6.14, (p.138), while a best-fit power law on our data with index 3.4 ± 0.1 will extrapolate to be higher than the maximum low energy flux from three sources combined (as reported by UHURU), a best-fit exponential spectrum with kT ~ 17 keV is quite consistent with the minimum UHURU intensity, again the sum of the three sources. Because of the possibly irregular variability of the three sources, it is difficult to estimate the relative
Fig. 6.14 Spectrum of the galactic center source complex. Error bars and upper limits shown are of lo. MIT data are taken from Ricker et al. (1973a) and Ricker et al. (1974). UCB data is taken from Mahoney (1973). Best-fit spectra are represented by solid and broken lines with their corresponding spectral characteristics indicated.
Figure 6.14
contributions from individual sources to our measurement according to previous measurements.
CHAPTER VII

CONCLUSIONS

7.1 SUMMARY OF OBSERVATIONAL RESULTS

The successful balloon-born observation has provided a hard x-ray survey of the galactic plane near the central portion of our galaxy. Most of the eleven observed sources could be identified with known strong sources in soft x-rays. Many of these sources have been observed in hard x-rays before, but this experiment has extended their spectra to energies as high as 500 keV. Two sources, CEN X-5 and GX 357+2.5 were measured in hard x-rays for the first time. One source, GX 331-1, could be an entirely new source. A tabulation of their measured intensities is given in Table 7.1, (p.141).

Assuming that the identifications put forth are correct, all eleven sources that we have observed lie within 5° of the galactic plane (equator) and are presumably located within the galaxy. Yet, being among the lesser-known half of the two dozen or so hard x-ray sources so far observed by balloon or satellite instruments [Peterson (1973)], there are no firmly established optical or radio counter-parts for any of them despite some suggestions [e.g. Lillier (1972)]. Available pertinent parameters concerning these sources, measured or estimated from x-ray data, are collected in
Table 7.1

<table>
<thead>
<tr>
<th>Peak Source</th>
<th>Photon Flux (phots/cm²-sec-keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-------------</td>
<td>-----------</td>
</tr>
<tr>
<td>α</td>
<td>1.74</td>
</tr>
<tr>
<td>β</td>
<td>4.86</td>
</tr>
<tr>
<td>γ</td>
<td>1.41</td>
</tr>
<tr>
<td>δ</td>
<td>5.38</td>
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<tr>
<td>ε</td>
<td>3.50</td>
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<tr>
<td>γ</td>
<td>1.46</td>
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<td>θ</td>
<td>5.06</td>
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<tr>
<td>ψ</td>
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<tr>
<td>φ</td>
<td>18.6</td>
</tr>
<tr>
<td>χ</td>
<td>21.9</td>
</tr>
<tr>
<td>γ</td>
<td>11.2</td>
</tr>
</tbody>
</table>

* Due to background subtraction
Table 7.2, (p.143), together with derived parameters from our measurement. The scanning program of our observation did not provide continuous coverage of any source so that short-term variability or flare activities could be determined. In view of the known variability of GX 301-2, GX 304-1, and GX 349+2 in hard x-rays and of almost all of these sources in soft x-rays, it is quite conceivable that at least some of the derived spectra are averages of varying spectra over the observation time. At any rate, these spectra show some interesting implications regarding galactic x-ray sources.

7.2 IMPLICATIONS OF OBSERVATIONAL RESULTS

As is evident from Table 7.2, (p.143), as well as from the discussions of the individual sources (cf. Section 6.2), the hard x-ray and soft x-ray measurements of the same source are often not compatible with each other in terms of spectral characteristics or both. This could possibly be an apparent phenomena caused by the variability of the source and nonsimultaneity of the measurements. But in some cases it could very well be an indication that the hard and soft x-ray emission are more or less independent of each other: either by different production processes or from separate emission regions. For instance, it seems that the hard x-ray spectra below 100 keV usually call for temperature typically several times higher than that derived from soft x-ray measurements when a thermal model is assumed, such as in the case of NOR X-1. This could be explained by the existence of a hard
Table 7.2

<table>
<thead>
<tr>
<th>SOURCE NAME</th>
<th>3U DESIGNATION</th>
<th>2-6 keV (1)</th>
<th>1-20 keV</th>
<th>DISTANCE (kpc)</th>
<th>15-100 keV</th>
<th>PRESENT WORK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kT (keV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td>a</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

| CEN X-5     | 1145-61        | 3.6         | 5        |                | 10±7        | 0.188        |
| GX 301-2    | 1223-62        | 6±1         | 4.8±0.4  |                | 6.1±4.8     | 11.5         |
| GX 304-1    | 1258-61 47/5  | 9.4±36      | 1.2      |                | 22±1       | 29.9         |
| CIR X-1     | 1516-56 720/20 | 3.7         | 2.93     | 8               | 57±13       | 4.4          |
| NOR X-2     | 11.4           |            |          |                | 12±2        |              |
| GX 331-1    | (22-95 keV)    | 25±3        | 1.31     | 3.0±0.3        | (22-75 keV) |
| NOR X-1     | 1630-47 150/3  | 6.1         | 0.6      |                | 15±2        | 1.75         |
| GX 340+0    | 1642-45 381/3  | 3.8         | 2.25     | 13              | 19±2        | 0.0073       |
| GX 349+2    | 1702-36 715/2  | 5.8         | 1.80     | 8               | 30±4        | 2.16         |
| GX 357+2.5  | 4.8           | 2.10        |          |                | 24±3        | 1.51         |
| GX 1+4      | 1728-24 60     | 18±2        | 1.6±0.2  |                |             |              |
| GX 3+1      | 1744-26 460/3  | 12          | 1.3      | 4               | 17±1        | 58.1         |
| GX 5-1      | 1758-25 1127/2 | 12          | 6.5±1    |                |             |              |

(1) From 3U catalog [Giacconi et al. (1973)]: Max. count-rate/variability factor
x-ray component in the emission, which is not a simple extension of the soft x-ray spectrum.

On the other hand, the hard x-ray spectra themselves are not always consistent with simple models. For instance, there are possible "breaks" in some of the spectra. And it is particularly interesting to note that there are three sources -- NOR X-2, GX 331-1, and GX 340+0 -- that have complex hard x-ray spectra showing a possible similarity to that of SCO X-1, i.e. hardening of spectrum as energy increases or having "excess" (from a separate component) over a thermal bremsstrahlung spectrum. All of these spectra are considerably harder than that of SCO X-1; hence the temperatures implied are two to four times higher. This might suggest that they belong to the same class of objects as SCO X-1, although the lack of optical or radio identification prevents any broad-base comparison and makes this nothing more than a possibility.

Since almost all the photon spectral distributions that we measured appear to be monotonic for energies lower than 100 keV, it is possible to use a power law spectral index $\alpha$ as an approximate measure of spectral hardness below 100 keV and produce a frequency distribution of $\alpha$ for the observed sources, as shown in Fig. 7.1(a), (p.145). The distribution spreads between two and six with most of the sources having $\alpha$ values between 3 and 4.5, thus putting the average at 3.9. It might not be a coincidence that the three sources that show possible similarity to SCO X-1 group...
Fig. 7.1  

(a) The frequency distribution of hard x-ray (<100 keV) spectral indices for 10 observed x-ray sources. Power low spectra are assumed. (The two in parentheses have large uncertainties involved.)

(b) The intrinsic x-ray luminosities (derived in soft x-ray measurements of Seward et al. (1972) of five sources versus their hard x-ray (<100 keV) spectral indices.
themselves together in the vicinity of the average value. CIR X-1, which is suspected to be similar to CYG X-1, stands out at the low end, while the interesting GX 301-2 is at the other extreme. It must be emphasized, however, that because of the temporal variability involved, the $a$ values as determined in this experiment are not necessarily typical of the hard x-ray spectra of these sources, even in cases where good agreement are found with previous measurements. In other words, the distribution of $a$-values might be a changeable one.

As a result of a complete soft x-ray survey of galactic sources, Seward et al. (1972) proposed the existence of two distinct types of stellar x-ray sources, i.e. not supernova remnants. One type, characterized by luminosities of the order of $10^{38}$ erg/sec, lies within about 5 kiloparsecs of the galactic center and all of its members have been observed at least in soft x-rays. The other type, probably much more numerous, are weaker sources having intrinsic luminosities of the order of $10^{36}$ to $10^{37}$ erg/sec; its members seem to be located in the outer spiral arms and only those within a distance of about 5 kiloparsecs from the solar system have been observed, mostly in soft x-ray (cf. Fig. 1.3, p. 10). Figure 7.1 (b) (p. 145) shows a plot of intrinsic soft x-ray luminosities, taken from Seward et al. (1972), versus hard x-ray spectral indices $a$ for five sources, three of the "first type" and two of the "second type". The intrinsic x-ray luminosities are derived from soft x-ray observations
and assumed density of interstellar matter in the direction of the respective sources. With the few examples available and the uncertainty in the luminosities*, it is difficult to find any definite implications except that there seem to be wide ranges of \( \alpha \)-values for both "types" of sources. But when the hard x-ray luminosities of these sources are compared with their intrinsic x-ray luminosities derived from soft x-ray observations, there seems to be some regularity involved (Fig. 7.2, p.148). At least for the three "strong" sources, the ratios of soft to hard x-ray luminosities are quite similar. The hard x-ray luminosities are derived from measured intensities between 40 and 500 keV, using the same source distances given in Seward et al. (1972).

On the other hand, all of the sources of the first type as suggested by Seward et al. (1972) have been scanned during out observation and the fact that half of them (GCX, GX 9+1, GX 13+1, GX 17+1) were not observed shows that these sources must have much softer overall x-ray spectra, i.e. much lower hard x-ray flux, than the observed ones (CIR X-1, GX 340+0, GX 349+2, and perhaps GX 5-1) at the time of our measurement. Based on our measurement, it seems that as a class their overall x-ray spectral hardnesses must differ considerably among themselves, at least between the observed group and the unobserved ones. Just

*The derived values should be regarded as upper limits since no self-absorption at the sources or their immediate surroundings were considered in the derivation.
Fig. 7.2 The hard x-ray luminosities (derived from the present work in the energy range 40 to 500 keV) of five observed sources versus their luminosities derived from soft x-ray measurements [Seward et al. (1972)] and the ratio between the latter and the former. Square boxes show the estimated values of luminosities and filled circles indicate the ratio.
like the class of intrinsically weaker sources. Furthermore, similar spectral features appear in spectra of both strong and weak sources, as in the cases of GX 340+0 and NOR X-2. Therefore, as far as hard x-ray spectra are concerned, there does not seem to be marked differences, perhaps no difference at all, that could be used to characterize the two proposed distinct types.

7.3 NEED FOR FURTHER OBSERVATIONS

The result of our experiment has shown that hard x-ray emission is quite common among galactic x-ray sources and that some sources have interesting spectral features at high energies that might separate them from the others. At this stage, the lack of simultaneous measurements of these sources in a wide range of photon energies, including optical and radio, makes precise theoretical considerations difficult, if not impossible. Any model put forth for the sources on the basis of either soft or hard x-ray measurement alone would at best be speculative; it is therefore evident that more observations in extended energy ranges are needed. In particular, simultaneous soft x-ray and hard x-ray observations would be extremely useful to establish spectral and temporal correlations between the two adjacent energy bands. A time history of the total x-ray spectrum would not only erase any possible discrepancies such as those discussed earlier, but could also provide an important handle to gain insight into the x-ray production at the source. At present,
balloon-borne hard x-ray telescopes would be ideal partners for satellite-borne soft x-ray telescopes in this task. Besides, hard x-ray telescopes with higher sensitivity and better angular resolution for photon energy up to about 1 MeV should be used to provide more observational data on individual sources. Essential in detecting temporal variation as well as precise spectrum determination, high sensitivity could best be achieved by using large sensitive area, either in single or multiple detector systems. Two difficult aspects, improvement of angular resolution and reduction of instrumental background level, might require breakthroughs in detector design. Although some innovative ideas have been suggested [e.g. Morfill and Pieper (1973)], substantial progress has yet to be seen in actual development. For long-term variations, as in the cases of GX 301-2 and GX 304-1, more frequent balloon observations would prove to be profitable before satellite-borne hard x-ray telescopes, such as those planned for the High Energy Astronomical Observatory series [e.g. Matteson (1973)], go into successful operation.
The report of detection of a 476 keV gamma ray line in the high energy photon spectrum from a localized source near the galactic center [Johnson and Haymes (1973)] and the subsequent diverse theoretical interpretations of this observation (cf. Section 1.2.1, p. 20) have prompted us to search our data for indications of extraterrestrial gamma ray line near 0.5 MeV.

Because of (1) the limited energy resolution of the spectrometer (30% FWHM at 0.5 MeV; cf. Figure 3.2, p.42), (2) the presence of the atmospheric 0.511 MeV gamma ray line (Fig. 4.4, p. 66), and (3) the sky coverage of our scanning program, the following approach was used to determine whether there is extraterrestrial line contribution near 0.5 MeV in the count-rate spectrum collected from a certain direction in the sky. A parameter L, defined as

\[ L = \frac{R(0.40 \text{ MeV} \sim 0.65 \text{ MeV})}{R(0.25 \text{ MeV} \sim 0.40 \text{ MeV}) + R(0.65 \text{ MeV} \sim 1.5 \text{ MeV})} \]

where \( R(E_2 \sim E_1) \) is the total number of counts in an energy interval \([E_1, E_2]\) in the collected count-rate spectrum, is used as a relative measure of possible gamma ray line contribution in the energy range of 0.40 MeV to 0.65 MeV over the continuum (cf. Appendix C, p.182) in the broader energy range of 0.25 MeV to 1.5 MeV. Both the 0.511 MeV (>95%) and the 0.476 MeV (>85%) gamma lines are included in the central energy interval.
A larger L value in a particular direction would mean enhanced strength in the 0.511 MeV line, or appearance of additional gamma lines (e.g. the 0.476 MeV line) between 0.40 MeV and 0.65 MeV, or less probably, a change in the continuum portion of the spectrum as a function of pointing direction. Possible effects of vertical altitude and azimuthal direction on the value of L cannot be separated and hence cannot be ruled out.

The portion of the sky scanned during the whole flight was divided into two-dimensional bins in three steps: first, small bins of average size of 2.5° x 2.5°, second, medium bins of average size of 5° x 5°, each formed from combining four small bins, and finally, large bins of average size of 15° x 15°, each formed from nine medium bins. 15° is approximately one-third of the FWHM in angular resolution of the telescope at 0.5 MeV. In each step, an L value is calculated for the spectrum collected from all instances when the telescope was pointing at directions inside a given bin, and the frequency distribution of all L values from different directions in the sky examined. The sky map of 22 large bins and their corresponding L values, as well as the frequency distribution of L-values are shown in Figure S.1 (p.153).

Both the frequency distributions for small and medium bins are consistent with normal distributions with the same mean value ($\bar{L} = 0.465$), but with the standard deviation of the latter (0.011) approximately half of that of the former (0.020). This indicates that random error is mainly responsible for the broadening. And by simple extrapolation, we have, in the
Fig. S.1 The sky map of L values for large bin divisions. The definitions of the spectral parameter L is graphically illustrated in the upper left corner. The L value and the observation time (in parentheses) associated with a given bin is shown inside the bin. The frequency distribution of the L values from all bins is in the upper right corner.
idealized distribution for the large bins, mean value

\[ \bar{L} = 0.465 \]

and standard deviation

\[ \sigma_L = \frac{0.048}{(2.35)(6)} = 0.034, \]

since every large bin is made up of 36 small bins. Therefore, with an average value of \( R(0.40 \text{ MeV} - 0.65 \text{ MeV}) = 25 \) counts per second, which is assumed to represent null flux in extraterrestrial line contribution, we obtain from the equation

\[ \Delta R = R \frac{\Delta L}{L} \]

and the photopeak efficiency of the detector at 0.5 MeV (48%) a 2σ value of \( 1.7 \times 10^{-3} \) photons/cm² per second as the limit in measurement sensitivity for the large bins. The same value will also serve as an upper limit for extraterrestrial contribution of gamma line near 0.5 MeV from most of the celestial area covered by our observation including the entire galactic plane from \( \ell^\text{II} = 280^\circ \) to \( \ell^\text{II} = 30^\circ \). It is interesting to note that the large bin centered at the source GX5-1 and containing the galactic center has a \( L \)-value of 0.476, which is almost 3σ above the mean value and corresponds to an "excess" gamma line flux of \( (3.1 \pm 1.5) \times 10^{-3} \) photons/cm² per second at 476 keV. Although this value should be regarded as an upper limit because of the nonseparable systematic effects discussed earlier, it is not inconsistent with the reported flux of \( (1.8 \pm 0.5) \times 10^{-3} \) photons/cm² per second of the 476 keV line from this region [Johnson and Haymes (1973)].


Klein, O., and Y. Nishina, Z. Physik 52, 853 (1928).


Lillier, W., Tabulation of Interesting Optical and Radio Sources near UHURU X-ray Sources, Private Circulation (1972).


Peterson, L. E., D.A. Schwartz, and J. C. Ling, Spectrum of Atmospheric Gamma Rays to 10 MeV at $\lambda = 40^\circ$, J. Geophys. Res. 78, 7942 (1973).


Appendix A

X-Ray and γ-Ray Production Mechanisms

Under various astrophysical conditions, a considerable number of processes could be responsible for x-ray or γ-ray production, resulting in different emission spectra. Possible mechanisms which have been discussed by various authors can be classified as in the following:

Thermal processes
- Hot, thin plasma
  - Thermal bremsstrahlung
  - Radiative recombination
  - Atomic line emission
- Hot, thick plasma ——— Blackbody radiation

Non-thermal processes
- Synchrotron radiation (magneto-bremsstrahlung)
  - Inverse Compton scattering
  - Compton-synchrotron process
- Non-thermal bremsstrahlung
- Proton inner bremsstrahlung
- Charge exchange
- Transition radiation

Nuclear processes
- Spontaneous nuclear decay
- Nuclear de-excitation
- Particle annihilation

Processes that are more important in consideration of x-ray sources will be discussed in detail in this appendix.

A.1 THERMAL PROCESSES

Thermal processes refer to atomic x-ray production processes in astrophysical plasmas in which various particle populations are in thermodynamic equilibrium with each other and a temperature can be defined. Both electrons and ions
have Maxwellian velocity distributions. The processes involved are thermal bremstrahlung (free-free transition), radiative recombination (free-bound transition), and line emission (bound-bound transition). The emerged high-energy photon spectrum depends not only on the temperature of the plasma, but also on its optical thickness in the frequency (or energy) range in question.

a) **Optically thin, hot plasma** - When the emission region is transparent enough to x-rays, it can be assumed that no generated photons will interact with the thermal medium. In this case the three emission processes are independent of each other, and the temperature of the plasma will determine their relative importance.

1. **Thermal bremsstrahlung** - Bremsstrahlung refers to the free-free transition of an electron accelerated in a Coulomb field. The process is efficient in energy transfer so that non-relativistic electrons become important and electrons with energy \( E = (1 - \beta^2)^{-1/2} m_e c^2 \) will lose energy through this kind of radiative collision at a rate

\[
- \frac{dE}{dt} = \frac{32\pi}{3} \frac{Z^2 e^6}{h m_e c^2} g n_z
\]

with \( n_z \) = density of ions with charge \( Z \) [Heitler (1960)].

Assuming a Maxwellian distribution for the electron population of density \( n_e \)

\[
\frac{d}{dE} \left( \frac{dN}{dV} \right) = \frac{2n_e}{(kT)^{3/2}} \left( \frac{E}{e} \right)^{1/2} e^{-E/kT}
\] (A.1)
the photons emitted will have a differential photon spectrum of the form

\[
\frac{dq}{dhv} = n_e n_z \frac{64\pi Z^2 e^6}{3h(m_e c^2)^2} \left( \frac{\pi m_e c^2}{6kT} \right)^{1/2} \frac{g(v,T)}{hv} \left(-\frac{hv}{kT}\right) \tag{A.2}
\]

where \(g(v,T)\) is the averaged Gaunt factor for free-free emission [Karzas and Latter (1961)]:

\[
g(v,T) = \begin{cases} 
\frac{3}{\pi} \ln \frac{4kT}{\hbar v} & \text{for } hv \ll kT \\
1 & \text{for } hv \gg kT,
\end{cases}
\]

with \(\ln \Gamma = 577\), and \(n_e n_z = 1.34 n_e^2\) assuming cosmic abundances of the elements.

2. **Radiative recombination** - This is the photon resulting from captures of free electrons by ions upon collision. By an approximation using hydrogen states of quantum number \(n\) [Elwert (1954)], a Maxwellian distribution of electrons (Equation A.1) captured by ions of charge \(Z\) will produce a differential photon spectrum of the form

\[
\frac{dq}{dhv} = n_e n_z \frac{4a I_H^2 Z^4}{(m_e c^2)^3} \left( \frac{\zeta_n}{2n} \right)^2 \left( \frac{m_e c^2}{2\pi kT} \right)^{3/2} e^{-\frac{(I_{zn} - hv) / kT}{2\pi kT}} \tag{A.3}
\]

where \(a = 2.11 \times 10^{-22} \text{ cm}^2\),

\(I_H\) = ionization potential of the nth hydrogen state,

\(I_{zn}\) = ionization potential of the nth state of the ion with charge \(Z\),

\(\frac{\zeta_n}{2n^2}\) = incompleted fraction of the nth shell.
3. **Atomic line emission** - This is the result of inelastic electron-ion collision in which the ion is excited and later de-excite by emission of a photon of discrete energy. For a Maxwellian distribution of electrons (Equation A.1), the intensity in a spectral line of energy $E_{nn'}$ corresponding to the $n-n'$ transition is

$$\frac{dq}{dhv} = n_e n_z 8\pi^2 e^4 f_{nn'} \bar{g}_{nn'} \left(6\pi m_e kT\right)^{-1/2} E_{nn'}^{-1} e^{-E_{nn'}/kT}$$

(A.4)

where $f_{nn'}$ = dipole oscillator strength for the $n-n'$ transition, $\bar{g}_{nn'}$ = averaged Gaunt factor for bound-bound transition [van Reyenmorter (1962)].

For an optically thin plasma of temperature below $5 \times 10^6 \, ^\circ K$, line emission is the dominant emission mechanism but subsides rapidly with increasing temperature. At about $10^7 \, ^\circ K$, line emission falls an order of magnitude below the bremsstrahlung process which becomes dominant [Tucker and Gould (1966)]. Radiative recombination is relatively unimportant in both temperature ranges. For most practical applications on cosmic x-ray sources, the temperature involved are at least of the order of $10^7 \, ^\circ K$ and therefore thermal bremsstrahlung is considered to be the representative emission process in a hot thin plasma.

b) **Optically thick, hot plasma (Blackbody radiation)** - A plasma that is hot, but optically thick, i.e. opaque, to x-rays can be approximated by a blackbody in which the photon field is in equilibrium with matter and has a differential photon density of the form
All three aforementioned emission processes are involved but are mutually coupled such that the emerged spectrum appears as a continuum and is a function of temperature only.

A.2 NONTHERMAL PROCESSES

Nonthermal processes are mostly non-atomic and non-nuclear processes in which the particle population involved does not have a Maxwellian distribution.

a) Synchrotron radiation - When relativistic electrons are accelerated in a magnetic field, energy is released in the form of electromagnetic radiation. An electron of energy \( E_e = \gamma m_e c^2 \) spiraling in a randomly oriented magnetic field of strength \( B \) will lose energy at the rate of

\[
\frac{dE_e}{dt} = \frac{\sigma_o c}{6\pi} B^2 \gamma^2,
\]

where \( \sigma_o \) is the Thomson cross section, and produces a photon spectrum which peaks strongly at the critical frequency

\[
\nu_c = \frac{3eB\gamma^2}{4\pi m_e c}
\]

and can hence be approximated by

\[
\frac{d}{dhv} \frac{dE_e}{dt} = \frac{dE_e}{dt} \frac{\delta(h\nu - h\nu_c)}{\delta(h\nu - h\nu_c)}
\]

For a constant and isotropic injection electron spectrum of
a power law form

\[ \frac{d}{dE_e} \left( \frac{dN_e}{d\nu} \right) = A E^{-\alpha}, \]

(A.9)

the emitted photon spectrum will be

\[ \frac{d\nu}{d\nu} = \frac{\sigma_o \lambda c B^2}{12\pi (m_e c^2)^2} \left[ \frac{h\nu}{\left( \gamma m_e c^2 \right)^2} \right] \left( \frac{a-3}{2} \right)^{-\frac{(a+1)}{2}} (h\nu) \]

(A.10)

The synchrotron process has been successfully utilized to account for radio emission from nonthermal radio sources and is a possible production mechanism for x-ray sources having power law spectra.

b) Inverse Compton scattering - When relativistic electrons and a low energy photon field (e.g. visible star light) are present simultaneously, collisions between a relativistic electron of energy \( \gamma m_e c^2 \) and a low energy photon of energy \( h\nu_o \) results in the transfer of energy from the electron to the photon and raise its energy to

\[ h\nu = \frac{4}{3} \gamma^2 h\nu_o \]

(A.11)

In a succession of similar collisions, the electron will lose energy at the rate of

\[ \frac{-dE_e}{dt} = h\nu \frac{dN_C}{dt} = \frac{4}{\gamma^2 \sigma o \nu_o} \]

(A.12)

where \( \frac{dN_C}{dt} = \) rate of collision

\( \sigma o = \) Thompson cross-section

\( \nu_o = \) energy density of the photon field
Thus for an input electron spectrum of power law form, the emission photon spectrum will be

$$\frac{dq}{d\nu} = \frac{2a_0 A e \rho}{3 (m_e c^2)^2} \left[ \frac{4h\nu}{3 (m_e c^2)^2} \right]^{\frac{a-3}{2}} - \left( \frac{a+1}{2} \right) (h\nu)$$

which has the same index as in the synchrotron case.

It is possible that both the synchrotron and Compton processes occur in the same emission region, either independently by the same electron population, provided both magnetic field and an external photon field are present; or operate in a consecutive manner when only the magnetic field is important. The latter case is a bootstrapping mechanism in which the synchrotron process produces the low energy photon field, then the same electron population will raise the photon energy to that of x-rays through inverse Compton scattering. In either case, the emerged x-ray spectrum will have the same power law index as in the case of simple synchrotron or simple Compton scattering.

c) Nonthermal Bremstrahlung - A power law electron distribution in an optically thin plasma will produce bremsstrahlung x-rays with a power law spectrum. The x-ray spectral index will be nearly equal to the electron spectral index for electron indices $\xi_2$ [Lin and Hudson (1971)].

A.3 NUCLEAR PROCESSES. Nuclear processes are the origin of monoenergetic $\gamma$-ray emission, the presence of which is determined by the nature and history of the source region.

a) Spontaneous nuclear decay - Unstable isotopes produced
in explosive nucleosynthesis in highly-evolved stars will decay at various rates depending on their half-lives. In a Type I supernova products from the \( \gamma \)-process will emit many gamma lines in the 30 keV to MeV energy range [Clayton and Craddock (1965)], while those from silicon-burning process will provide lines between 300 keV to 3.26 MeV [Clayton, Colgate and Fishman (1969)].

b) **Particle annihilation** - This includes \( \pi^0 \) decay and positron-electron annihilation. Both neutral pions and positrons are produced in collisions between primary cosmic rays and nuclei in the interstellar medium. The \( \pi^0 \) has a mass of 135 MeV energy equivalent, a mean life of about \( 10^{-16} \) sec and decays into two gamma photons (98.8%). A positron will annihilate with an electron at any energy or through the formation of an intermediate bound state — positronium. In either case, the annihilation could result in two or three gamma photons, but the two photon process dominates the annihilation of free electron-positron pairs (99.7%) [Stecker (1969)]. If the pair is at rest, the result is two 511 keV photons; otherwise one photon will possess most of the energy of the electron-positron system, while the other carries an energy between 250 keV to 500 MeV [Heitler (1960)].

c) **Nuclear de-excitation** - Interaction of primary cosmic ray with interstellar medium can produce excited nuclei which then de-excite by emitting characteristic \( \gamma \)-rays. For example, excited \( \text{Li}^7 \) will emit \( \gamma \)-rays of energies 478 and 432 keV [Fishman and Clayton (1972)].
Appendix B

Photon-Matter Interactions

In traversing any form of matter, high-energy electromagnetic radiation behaves like particles (photons) and undergoes three kinds of interactions: photoelectric effect, Compton scattering, and pair production. The relative importance of these interactions depends on both the energy of photons involved and the atomic number $Z$ of the matter through which the photons propagate. The net effect is the attenuation of the traversing radiation by the absorbing matter.

a) Photoelectric effect - This is a collision between an incident photon and a bound electron which results in a complete energy transfer. The electron is ejected carrying an energy of $E - E_n$ where $E$ is the photon energy and

$$E_n = \frac{R \hbar c (Z-\sigma)^2}{n^2}$$

is the binding energy of the nth-shell electron.* The atom, left in an excited state, will de-excite by emission of either a fluorescent x-ray photon or an Auger electron with energy $E_n$. The fluorescent x-ray photon can be absorbed in a similar manner and thus the incident photon is totally absorbed. The energy $(E - E_n)$ carried by the photoelectron will be consumed in forming ion pairs along its track in the absorber. But if the interaction occurs near the boundary of the absorbing matter, the fluorescent x-ray photon,

* $R$ is the Rydberg constant
or even the photoelectron, could escape so that only part of the energy \( E \) is deposited in the absorber.

The cross-section of photoelectric effect has a strong and complex dependence on \( Z \) and \( E \) [Davisson & Evans (1952)], yet in a simplified form

\[
\sigma_p = \frac{Z^a}{EB} \tag{B.2}
\]

where \( a = 4 \sim 5 \) and increases with \( E \), and

\[
b = \begin{cases} 
3 & E < 200 \text{ keV} \\
1 & E > 500 \text{ keV} 
\end{cases} 
\]

This implies that photoelectric effect is more important for low energy photons in high \( Z \) absorbers.

b) **Compton Scattering** - This is an elastic collision in which a photon transfers part of its energy \( E \) to a free electron in the absorber and is scattered at an angle \( \phi \) from its incident direction with reduced energy

\[
E' = \frac{E}{1 + a (1 - \cos \phi)} \tag{B.3}
\]

The energy transferred to the electron, \( E_e \), also a function of \( e \) and \( \phi \), is given by

\[
E_e = E \left[ \frac{a (1 - \cos \phi)}{1 + a (1 - \cos \phi)} \right] \tag{B.4}
\]

In both equations,

\[
a = \frac{E}{m_e c^2}
\]

is the incident photon energy in units of the electron rest mass \( m_e \). Therefore, when

\[
\phi = 0^\circ, \ E' = E, \ E_e = 0 \\
\phi = 180^\circ, \ E' = \frac{E}{1 + 2a}, \ E_e = \frac{E}{1 + \frac{2a}{2a}}
\]
The photoelectron is scattered at an angle $\theta$ to the incident direction of the photon with

$$\tan \theta = \frac{\cot (\phi/2)}{1 + a}$$  \hfill (B.5)

and again might escape the absorber depending on its range in the given absorber and the size of the absorber.

The cross-section for Compton scattering is given by the Klein-Nishina formula [Klein & Nishina (1928)].

$$\sigma_c = 2\pi r_o^2 \left\{ \frac{1}{\alpha^2} \left[ \frac{2(1+2)}{1+2\alpha} - \frac{1}{\alpha} \ln (1+2\alpha) \right] + \frac{1}{2\alpha} \ln (1+2\alpha) - \frac{1+3\alpha}{(1+2\alpha)^2} \right\}$$  \hfill (B.6)

where $r_o = \frac{e^2}{m_e c^2}$ is the classical electron radius. In general, $\sigma_c$ decreases with increasing energy but at a much slower rate than photoelectric effect.

c) **Pair Production** - This is the transformation of a high-energy photon into an electron-positron pair in the presence of a nucleus, which help to fulfill the conservation of both energy and momentum. The threshold photon energy of this process is $2 m_e c^2 = 1.022$ MeV in the center-of-mass system and is almost the same in the laboratory system for production near a nucleus.

The produced positron will probably annihilate with an electron, generating either two 0.511 MeV photons or three photons of different energies. The absorption of the incident photon will be total unless one or more of the annihilation photons (or the electron or positron for that matter) escape the absorber. Being nonzero for energies above the threshold, the cross-section of pair production increases rapidly with energy until it reaches a plateau value of the order of
in the GeV energy range.

In the energy range of 10 keV to 10 MeV, the dominance in interaction shifts from photoelectric effect to Compton scattering to pair production, as energy increases. The exact energies at which change-overs occur are different for different absorbing matter. But because the Compton cross-section is usually smaller than those of the other two processes, the total interaction cross-section, in most cases, has its minimum at an energy where the Compton process is dominant. A good illustration is found in Fig. 3.3 (p. 44) for the case of sodium iodide.

For any of the three processes, a single interaction will remove a photon from a collimated beam of photons and the probability of occurrence is proportional to both the interaction cross-section and the beam intensity. The propagation of a parallel beam through an absorbing medium will thus be described by

$$I(x) = I_0 e^{-(\mu_{pe} + \mu_{cs} + \mu_{pp})x}$$

where

$I(x)$ = beam intensity after traversing a thickness of $x$

$I_0$ = initial beam intensity

$\mu_i$ = interaction cross-section of the three processes as designated by the subscripts.
APPENDIX C

ATMOSPHERIC SECONDARY RADIATIONS

Various kinds of secondary radiation are produced continuously in the atmosphere as the result of the constant bombardment of high-energy cosmic ray particles. Fig. C.1 (p.183) [Peterson et al. (1973)] shows the major production processes and typical energy of particles involved in each step. These secondary protons, neutrons, electrons, x-ray and γ-ray photons constitute a menacing environment to which a detector-telescope, while committed to measure extraterrestrial radiation, is nevertheless sensitive. The neutral components, photons, and neutrons, prove to be most restricting for x-ray and γ-ray measurements because of their capability to penetrate shielding material or detector without interaction.

C.1 X-RAY AND GAMMA-RAY PHOTONS

High-energy photons in the atmosphere are produced by the following processes:

- bremsstrahlung from electrons (and positrons)
- positron-electron annihilation
- nuclear de-exitation
- π⁰ decay

But in the energy range of 10 keV to 10 MeV, only the first three are important [Puskin (1970)].
PRODUCTION OF SECONDARY RADIATIONS IN THE ATMOSPHERE BY COSMIC RAYS

PROCESS

PRIMARY COSMIC RAYS

ATMOSPHERIC NUCLEI

FRAGMENTS

ELECTROMAGNETIC CASCADE

DECAY


c_0

COMPTON

PAIR

0.5 MeV

PHOTOELECTRIC ABSORPTION

25 KeV

MULTIPLE COMPTON SCATTER

1 MeV

NUCLEAR γ-RAYS

10 MeV

50 MeV

200 MeV

TYPICAL ENERGY

3 BeV

Fig. C.1 Production processes of secondary radiations in the atmosphere induced by primary cosmic rays and typical energy of particles involved. Adapted from Peterson et al. (1973).
a) **Bremstrahlung from Electrons**

As is shown in Fig. C.1 (p.183), secondary electrons with energy of typically a few MeV are produced in $\nu^- -$ meson decay, electron-positron pair production, and Compton scattering. Precipitation of geomagnetically trapped electrons is another source. Free-free transition of these electrons in Coulomb fields is an efficient process in generating x-ray and γ-ray photons of a wide range of energies [Jackson, 1962], Chapter 15]. Positrons also contribute but they are much fewer in number [Beuermann (1971)]. Ninety percent of the atmospheric x-rays and γ-rays appear in a continuum energy distribution and over ninety percent of this continuum comes from electron (positron) bremstrahlung. The rest comes from Compton scattered monoenergetic γ-ray photons.

b) **Electron-Positron Annihilation**

Positrons are produced in $\nu^+ -$ meson decay as well as pair production. Electron-positron annihilation mostly leads to the production of two 511 keV photons (cf. Appendix A, p.170), some of which would degrade in energy via Compton scattering. As a result, the annihilation process gives rise to an outstanding gamma line at 511 keV and contributes to a few percent of the continuum.

c) **Nuclear De-excitation**

Interaction of atmospheric nuclei, mainly $N^{14}$ and $O^{16}$, with neutrons through either capture or inelastic scattering produces various excited daughter nuclei such as $N^{14}$, $N^{15}$, $B^{11}$, and $O^{16}$. All of them de-excite by emitting
one or more monoenergetic gamma photons with energies ranging from 0.728 to 10.83 MeV. [Peterson et al. (1973)]. The contributions of all the gamma lines add up to only a few percent of the total atmospheric high-energy flux.

Directly related to the primary cosmic ray fluxes, the flux (or intensity) of each component of atmospheric x-ray and \( \gamma \)-rays is a function of vertical altitude, zenith angle, geomagnetic latitude, and azimuth. But there are no comprehensive studies or measurement that show these factors independently in the energy range of 10 keV to 10 MeV. Fig. C.2 is a compilation of measurements of the atmospheric x-ray and \( \gamma \)-ray spectrum, made mostly by omnidirectional detectors at a typical balloon altitude (3.5 gm/cm\(^2\)) and at a geomagnetic latitude of 40°N. [Peterson et al. (1973); Klumpar et al. (1973)]. The fluxes shown are effectively equivalent omnidirectional fluxes, i.e. averaged over all zenith angles as well as azimuth. Theoretical studies have shown strong zenith angle dependence on atmospheric \( \gamma \)-ray fluxes between 300 keV and 10 MeV with upward-moving fluxes being highest throughout the energy range (Fig. C.3, p.187) [Ling (1974)], although one measurement in the same energy range showed that the highest fluxes come from the side -- "horizon brightening" effect [Scheel and Roehrs (1972)]. Because of the east-west asymmetry of cosmic-ray fluxes, atmospheric hard x-rays up to 150 keV have been observed to show a similar asymmetry in fluxes of a few percent [Agrawal (1972)]. A detailed study of the effect of altitude and geomagnetic
Fig. C.2 Omnidirectional spectrum of atmospheric x-rays and γ-rays at an altitude of 3.5 gm/cm² and a geomagnetic latitude of 40°N. Adapted from Peterson et al. (1973).
Fig. C.3 Calculated photon flux of atmospheric gamma rays from 0.3 MeV to 10 MeV as a function of zenith angle at an altitude of 3.5 gm/cm² and a geomagnetic latitude of 40°N. After Ling (1974).
latitude on atmospheric $\gamma$-ray fluxes in the energy range about 2 MeV have been given by Daniel and Stephens (1974). In general, the total fluxes increase with increasing altitude at altitudes above 100 gm/cm$^2$.

C.2 NEUTRONS

As is shown in Fig. C.1 (p.183) high-energy neutrons are produced in nucleonic cascades induced by primary cosmic rays. Various transport mechanisms then help to establish an equilibrium population of atmospheric neutrons having a wide range of energies. Just like atmospheric x-rays and $\gamma$-rays, the neutron flux is a function of altitude, zenith angle, geomagnetic latitude and probably azimuth. Fig. C.4 (p.190) shows the spectral distribution of albedo neutrons (upward moving) at the top of atmosphere from both theoretical [Lingenfelter (1963); Merker (1970)] and experimental [Jenkins et al. (1971); Freden and White (1962); Eyles et al. (1971); Heidbreder et al. (1970)] studies for the geomagnetic latitude of $\gamma = 40^\circ$. A comparison between Fig. C.2 (p.186) and Fig.C.4 (p.190) reveals that for energies below 10 Mev, neutron fluxes are lower than photon fluxes at balloon altitudes; between 10 MeV and 100 MeV, the two are more or less equal in intensity. Preszler et al. (1974) has provided a detailed measurement of the dependence of neutron fluxes on altitude and zenith angle in the energy range of 10 - 100 MeV. It is shown that above the altitude of 100 gm/cm$^2$, neutron flux decreases with increasing altitude and levels off above
10 gm/cm$^2$. But there are always more upward-moving neutrons than downward-moving ones, and this asymmetry grows with increasing altitude, with an up-down ratio of $\sim 3.5$ at typical balloon altitudes. Generally speaking, the total atmospheric neutron flux increases with increasing geomagnetic latitude [Jenkins et al. (1970); Holt et al. (1966); Simnett et al. (1972)].
Fig. C.4 Calculated and measured spectrum of albedo neutrons from the atmosphere at a geomagnetic latitude of 40°N. After Preszler (1973).
APPENDIX D

NUMERICAL EXAMPLES IN DERIVATION OF SOURCES
AND THEIR INTENSITIES

To illustrate the method of determination and separation of sources (Section 5.1.2, p.79), as well as the procedure in the derivation of primary spectra for the sources (Section 5.1.3, p.81), a section of Scan Band A containing three closely spaced sources is used as an example. The triangular patterns fitted to the count-rate profiles in four channel (or energy) intervals are shown in Fig. D.1 (p.192). In conjunction with Fig. D.1, Table D.1 (p.193) and D.2 (p.194) present, in a downward-flow manner, the numerical derivations performed for two energy intervals. The upper portion in each table shows how contributions from closely spaced sources are separated and the lower portion shows the steps of corrections that lead to the final values in the primary differential photon spectra of the sources. At each step the resulted values are shown.
Fig. D.1 The count-rate profile (thin solid line) of a portion of scan band A containing three closely spaced sources and the fitted triangular source patterns (heavy solid line). Vertical broken lines show the boundaries of spatial bins, and horizontal broken line show the estimated background levels.
### Table D.1

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<th>-2</th>
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<th>2</th>
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<th>5</th>
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</thead>
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<td>Observation time</td>
<td>t_i (sec)</td>
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<td>70</td>
<td>180</td>
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<td>260</td>
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<td>360</td>
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<td>340</td>
</tr>
<tr>
<td>Count-rate profile</td>
<td>(R+B)_(i) (count/ sec)</td>
<td>17.58</td>
<td>17.62</td>
<td>18.26</td>
<td>16.90</td>
<td>17.99</td>
<td>17.71</td>
<td>17.66</td>
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<td>a_i (sec)</td>
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<td>1</td>
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<tr>
<td>Differential photon flux</td>
<td>$j_k$ (photons) (keV cm$^2$ sec$^{-1}$)</td>
<td>$1.18 \times 10^{-4}$</td>
<td>$0.41 \times 10^{-4}$</td>
<td>$0.813 \times 10^{-4}$</td>
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