STUDIES OF DISCRETE COSMIC X-RAY SOURCES AT M.I.T.

(Invited Discourse)

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The following is a brief summary of some of the recent results obtained at M.I.T. which bear on the properties of various discrete X-ray sources, both galactic and extragalactic. Most of the work referred to has been described in publications which contain more complete descriptions.

1. Galactic Sources

In a July 1968 rocket observation with narrow slat collimators, Bradt *et al.* scanned the region of the Milky Way in the range of galactic longitudes from about $l^{\text{II}} = -20°$ to $+17°$ and in the energy range from 2 to 8 keV. They obtained a variety of results on the positions, angular sizes, and spectra of various sources. Their data confirmed the positions for the sources GX3+1, GX5−1, GX9+1, GX13+1, and GX17+2 [1] determined in their July 1967 flight [2]. The agreement between the previously and recently measured intensities of the sources north of $l^{\text{II}} = 0°$ indicated that they have not changed by more than 30% in over 2 years. Upper limits of 100 arc sec were placed on the angular sizes of four sources [3].

In a rocket flight on April 26, 1969 Bradt *et al.* observed a pulsating component of X-rays from the Crab Nebula [4]. The period and phase of the X-ray pulsations were the same as the optical pulsations of the pulsar NP 5032 which was observed nearly simultaneously at the MacDonald and Mt. Palomar Observatories. Details of this observation are presented elsewhere in this Symposium.

Rappaport *et al.* have developed a sensitive and reliable method for measuring the effects of interstellar absorption on X-ray spectra near 10 Å [5]. They employ proportional counters with thin (7.7 μ) aluminum windows that define two distinct spectral bands of sensitivity above and below the Al K-edge near 8 Å. Using data on the ratio of counts in these two bands obtained in their July 1968 flight that scanned the Scorpio-Sagittarius region, and their April 26, 1969 flight that measured the Crab Nebula pulsar, they measured or placed limits on the column density of atoms between the earth and several sources as summarized in Table I. Significant absorption was also observed in the spectra of several other of the Sagittarius sources. This recent work confirms and extends their earlier measurements of low energy spectra based on a July 1967 flight [6].

Bradt *et al.* have examined their rocket data on Sco X-1 for evidence of iron line emission. An upper limit of 1×10^{-8} ergs cm^{-2} sec^{-1} was set on the intensity of the iron K-line from Sco X-1 [6].

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TABLE I

Summary of results on
interstellar X-ray absorption

Source	Column density from earth to source (atoms/cm^2)
Sco X-1	$< 10^{21}$
Crab Nebula	$< 3 \times 10^{21}$
GX349 + 2	$\geqslant 1 \times 10^{22}$
GX5 − 1	$\geqslant 1 \times 10^{22}$

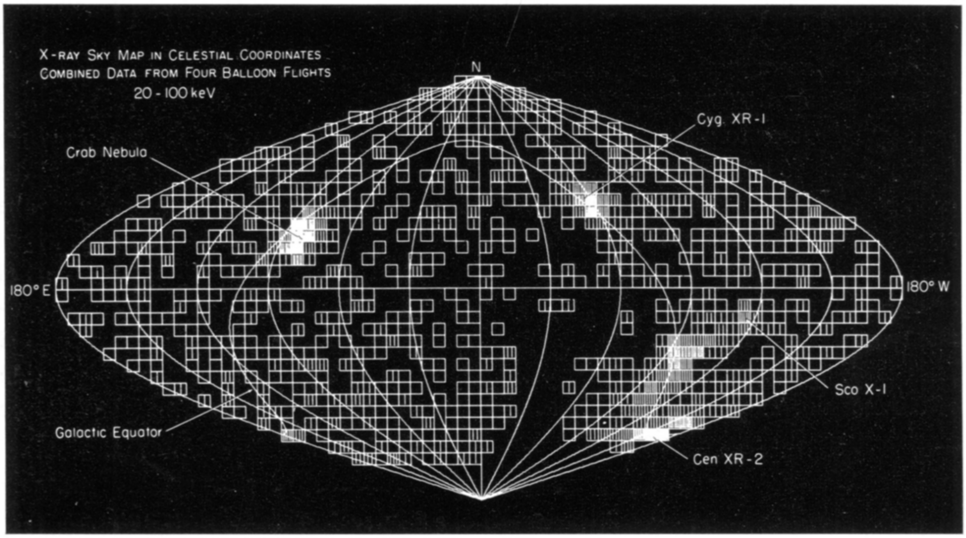

Fig. 1. Composite of four balloon surveys of cosmic X-rays above 20 keV. The number of bars in any given box is the number of statistical standard deviations by which the observed counting rate exceeds the background rate.

In the higher energy range accessible to balloon observations, Lewin *et al.* completed a general sky survey of X-rays above 20 keV with an angular resolution of approximately 10° FWHM. Figure 1 is a summary of their results from four flights in the form of a sky map which shows that all the prominent high energy sources are concentrated near the galactic equator. Only the Crab Nebula and Cyg X-1 stand out in the northern hemisphere. Detailed examination of the data obtained in flights in the southern hemisphere has led to the following results:

(1) An X-ray flare was observed from Sco X-1 on October 15, 1967 during a flight in Australia when the observed intensity in the energy range from 20 to 30 keV increased by a factor of 4 in less than 10 minutes and then decreased during the next 20 minutes [7]. The time structure of the X-ray flare resembled that of the optical flares previously observed, but its amplitude, measured both in terms of absolute

energy flux and fractional increase, far exceeded the amplitudes of any of the optical flares observed so far.

(2) Cen XR-2 was observed [8] during the October 15 balloon flight in Australia as an intense source above 20 keV shortly after it had gone undetected in a rocket experiment sensitive in the range 2–8 keV. A position determination was made with an error radius of $1.^\circ 5$. Within this circle Eggen *et al.* [9] reported the variable blue star WX Centauri which may be the optical counterpart.

(3) A possible decrease in the intensity of Cen XR-2 was noted between the October 15 flight and a subsequent flight 9 days later [10].

(4) Recent results from a balloon observation by Lewin *et al.* [24] on March 20, 1969 show that the intensity of Cen XR-2 had decreased by at least a factor of 7 since October 15, 1967.

(5) The data on a complex of high energy sources observed between $l^{\text{II}} = -40°$ and $+5°$ can be accounted for in terms of four discrete sources [11].

Overbeck and Tanenbaum [12] have conducted a series of balloon flights using the same detector to make precision measurements of X-ray fluxes in several energy bands above 15 keV. In the cases of both Sco X-1 and Cyg XR-2 they reported the occurrence of time variations by factors from 2 to 3 between measurements made approximately one month apart.

In a study of the angular sizes of high energy X-ray sources Floyd [13] has obtained an upper limit of 1.4 arc min for Cyg X-1 at energies above 20 keV in a balloon experiment with a gyrostabilized modulation collimator. Telemetry difficulties prevented full use of the capability of the instrument which has a potential angular resolution of 0.1 arc min. The Crab Nebula has been observed in a more recent flight with the same instrument and the data are now being analyzed.

2. Extragalactic Sources

With the most sensitive balloon and rocket instruments available to date, the minimum detectable X-ray energy flux from a discrete source lies in the range from 10^{-10} to 10^{-9} ergs/cm^2 sec. A flux in this range exceeds the radio energy fluxes of the brightest extragalactic (and galactic) radio sources by factors of 10 or more. Moreover, it exceeds the optical energy flux of a tenth magnitude object which would be among the brighter galaxies of the Virgo Cluster. Thus a valid observation of X-ray emission from even a relatively near exterior galaxy implies an astonishing non-thermal luminosity in the form of X-ray photons. Moreover, the detection of X-rays from any of the quasars (which are comparatively faint objects in the optical and radio regions, presumably because of their great distances) would imply that the emission is completely dominated by X-rays. There is reason, therefore to look very skeptically at any report of an extragalactic source which is based on an excess number of counts above background which is no more than three standard deviations of a Poisson distribution. Below this level of statistical significance the chances are dangerously large that a false signal will be found at one or another of the many potentially interesting positions scanned in a broad sky survey. When there are, in addition, significant systematic errors in the background rate evaluation, even greater caution is obviously necessary.

At the present time the X-ray source in Virgo is the only one which has been identified as an extragalactic object with reasonable certainty on the basis of rocket surveys [14, 15, 16] in the 1–10 keV region. These surveys showed signals with 3σ significance or better from a source located within a small region containing M-87 but otherwise devoid of conspicuous objects. Haymes *et al.* [17] recently reported a balloon observation of M-87 at energies above 30 keV which they interpreted as evidence for a continuation to 100 keV of the power law spectrum that fits the data for the emission of the jet from the visible to the soft X-ray region. In contradiction, McClintock *et al.* at M.I.T., using an oriented detector with 2000 cm^2 of sensitive area and an 8° FWHM field of view, found no significant evidence of a source of X-rays above 20 keV at the M-87 position [18]. If the results of Haymes *et al.* were correct, the M.I.T. experiment should have reported a 5σ peak. McClintock *et al.* have emphasized the need for great caution and precision in evaluating the background rate in a balloon experiment in which, as in the case of M-87, the signal is at best only a small percentage of the background rate. They did their evaluation by comparing the rates at nearby azimuths on either side of M-87. In contrast Haymes *et al.* evaluated the background only at an azimuth 180° from that of M-87.

There have been several reports of the detection of X-rays from other extragalactic sources, namely the radio galaxy Cyg A [18], the quasar 3C273 [15], and the Large Magellanic Cloud [19]. A subsequent survey of the Cygnus region by Giacconi *et al.* [20] placed an upper limit on Cyg A which contradicts the earlier claim.

The experiment of Bradt *et al.* [16], which placed M-87 in the 6 deg^2 uncertainty area around the measured position of the X-ray source, also scanned the position of 3C273 and found a 3σ upper limit consistent with the intensity claimed for it by Friedman *et al.* [15]. However, an optimal analysis of the raw data subsequently published by Friedman *et al.* [21], reveals that the counting rate peak attributed to 3C273 contained a number of counts above background which was less than one standard deviation of the Poisson distribution. Other similar criticisms of the 3C273 report have been made [22]. Therefore, at the present time, there is no significant evidence that X-rays have been detected from 3C273.

Finally, with regard to the Large Cloud of Magellan (LCM), consideration of the graphical display of the rocket data of Mark *et al.* [19] together with the information supplied with regard to the rate of scan shows that the excess of counts above background in this experiment was not more than two standard Poisson deviations and that the uncertainty in the location of the alleged source was relatively large. Therefore, their conclusion that the LCM has an X-ray luminosity in the 1–10 keV region equivalent to 100 Crab Nebulae does not appear to be well substantiated. It should be noted also that a 3σ *upper limit* of 120 Crab Nebulae was previously placed on the luminosity in the range 20–60 keV by Lewin *et al.* [23] on the basis of a balloon survey.

In the light of the weakness of the experimental evidence for the detection of extragalactic sources other than M-87 and considering the absolute X-ray luminosities that such sources must have to be detectable in current rocket and balloon experiments, it would appear that further substantial progress in the study of extragalactic X-ray sources may well be made only by the satellite experiments due for launching in 1970 and 1971.

References

[1] Mayer, W., Bradt, H. V., and Rappaport, S.: 1970, *Astrophys. J. (Letters)* **159**, L115.
[2] Bradt, H. V., Naranan, S., Rappaport, S., and Spada, G.: 1968, *Astrophys. J.* **152**, 1005.
[3] Polucci, G., Bradt, H. V., Mayer, W., and Rappaport, S.: 1970, *Astrophys. J. (Letters)* **159**, L109.
[4] Bradt, H. V., Rappaport, S., Mayer, W., Nather, R., Warner, B., MacFarlane, M., and Kristian, J.: 1969, *Nature* **222**, 728.
[5] Rappaport, S., Bradt, H. V., and Mayer, W.: 1969, *Astrophys. J. (Letters)* **157**, L21.
[6] Rappaport, S., Bradt, H. V., Naranan, S., and Spada, G.: 1969, *Nature* **221**, 428.
[7] Lewin, W. H. G., Clark, G. W., and Smith, W. B.: 1968, *Astrophys. J. (Letters)* **152**, L55.
[8] Lewin, W. H. G., Clark, G. W., and Smith, W. B.: 1968, *Astrophys. J. (Letters)* **152**, L49.
[9] Eggen, O. J., Freeman, K. C., and Sandage, A.: 1968, *Astrophys. J. (Letters)* **154**, L27.
[10] Lewin, W. H. G., Clark, G. W., and Smith, W. B.: 1968, *Nature* **220**, 249.
[11] Lewin, W. H. G., Clark, G., Gerassimenko, M., and Smith, W. B.: 1969, *Nature* **223**, 1142.
[12] Overbeck, J. W. and Tanenbaum, H. D.: 1968, *Astrophys. J.* **153**, 899.
[13] Floyd, F.: 1969, *Nature* **222**, 967.
[14] Byram, E. T., Chubb, T. A., and Friedman, H.: 1966, *Science* **152**, 66.
[15] Friedman, H. and Byram, E. T.: 1967, *Science* **158**, 257.
[16] Bradt, H. V., Mayer, W., Naranan, S., Rappaport, S., and Spada, G.: 1967, *Astrophys. J. (Letters)* **150**, L199.
[17] Haymes, R. C., Ellis, D. V., Fishman, G. J., Glenn, S. W., and Kurfess, J. D.: 1968, *Astrophys. J. (Letters)* **151**, L131.
[18] McClintock, J. E., Lewin, W. H. G., Sullivan, R. J., and Clark, G. W.: 1969, *Nature* **223**, 162.
[19] Mark, H., Price, R., Rodrigues, R., Seward, F. D., and Swift, C. D.: 1969, *Astrophys. J. (Letters)* **155**, L143.
[20] Giacconi, R., Gorenstein, P., Gursky, H., and Waters, J. R.: 1967, *Astrophys. J. (Letters)* **149**, L85.
[21] Friedman, H., Byram, E. T., and Chubb, T. A.: 1968, *Science* **159**, 747.
[22] Argyle, E.: 1968, *Science* **159**, 747.
[23] Lewin, W. H. G., Clark, G. W., and Smith, W. B.: 1968, *Nature* **220**, 249.
[24] Lewin, W. H. G., McClintock, J. E., and Smith, W. B.: 1970, *Astrophys. J. (Letters)*, March issue.