PROPERTIES OF INDIVIDUAL X-RAY SOURCES

(Invited Discourse)

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In the past 2 years the group at American Science & Engineering, Inc., including Gursky, Gorenstein, Kellogg and me, has been engaged in a program of rocket launches aimed at the solution of several outstanding questions in X-ray astronomy. Of four rocket launches, one was almost totally unsuccessful due to a mechanical failure; one was only partially successful due to a failure of the ACS (Attitude Control System); and two performed as planned. Notwithstanding the delays induced by this run of bad luck, a considerable amount of data has been gathered and analyzed. The major results obtained in the flights on October 11, 1966, and on February 2, 1968, have been published. It is my intent today to report on preliminary results of a recent flight (December 5, 1968) and briefly summarize conclusions from previous flights, and comment on a few selected topics to which this experimental program may contribute.

(1) The first objective of the program was to accurately locate X-ray sources and was prompted by the state of confusion still existing as late as 1966 on the location, intensity and variability of galactic X-ray sources. The successful identification of Sco X-1 had earlier convinced us of the need for accurate location. We set ourselves to the task of examining with as high a sensitivity and as high an angular resolution as possible several regions where numerous sources had been detected and to extend the survey to regions of the northern hemisphere not yet scanned at high sensitivity. We hoped that improved locations and decreased sources confusion would lead to new optical identifications and consequently to a better understanding of the nature and distance of individual sources.

(2) The second objective was to obtain more accurate spectra of the X-ray sources. We recognized that by use of proportional counters sensitive in the region from 1 to 10 keV we would not in many cases have a wide enough energy range to select the specific spectral shape for each source. We hoped, however, to be able to obtain relative spectral measurements which would allow us to distinguish the essential features of the different sources. Also, by observing the presence of low energy cutoffs, we might be able to ascribe distances to the sources based on the degree of interstellar absorption present.

(3) The third objective was to examine the distribution of the galactic X-ray sources in an effort to decide whether they would be assigned a type I or II distribution; whether in other terms, we were dealing with relatively young or relatively old objects.

(4) The fourth objective was to determine whether several objects which were considered likely candidates for X-ray emission, such as novae, supernovae, and radio sources, would, in fact, prove to be candidate objects when the precision of location of sources was increased by approximately one or two orders of magnitude.

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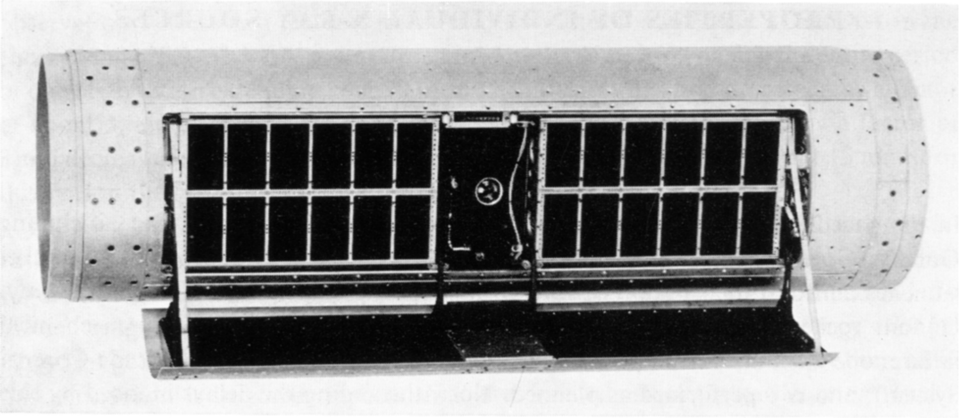

Fig. 1. X-ray astronomy payload for sounding rocket containing collimated proportional counters and aspect camera.

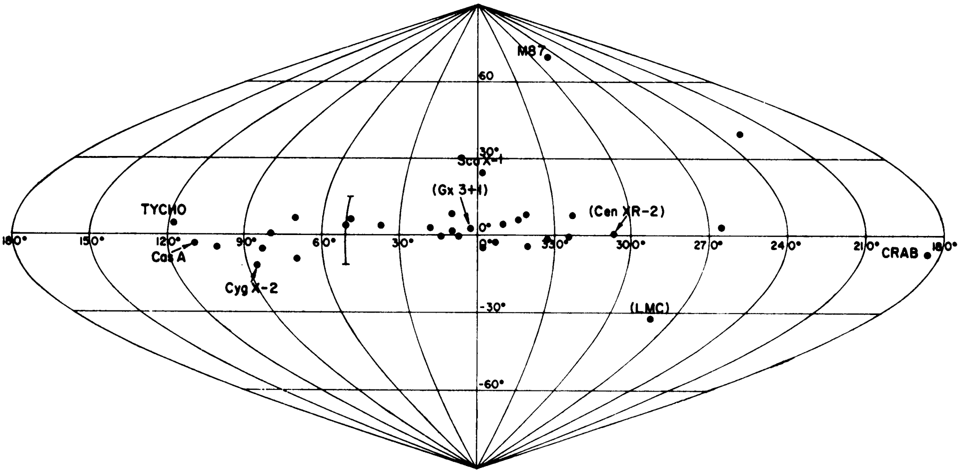

Fig. 2. The distribution of X-ray sources on a galactic coordinate system.

To accomplish these objectives we designed a rocket payload shown in Figure 1. This identical payload was flown, recovered, and reflown four times with only slight modifications. Details of the instrumentation have been described previously (Gursky *et al.*, 1968; Gorenstein *et al.*, 1969a, b). It consists of two large area banks of proportional counters with slit type collimators and an aspect camera to obtain aspect by photography of the star field in visible light. An attitude control system was used to permit us to scan a selected portion of the sky at a selected rate in the manner first used by Fisher. From the early flight of October 1966 to the last flight of December 1968, the only substantial modifications to the payload were the addition of PSD (pulse shape discrimination), which reduced the residual non X-ray background after anti-coincidence by a factor of 10, the use of a thinner window (1 mil Be, rather than 3) to extend the response to longer wavelength, and the use of two slits rather than one to reduce the maneuvers necessary to obtain positions for each source. Apart from the obvious convenience and economy of re-using the same payload, there is a very real advantage in determining the variability of sources by having a consistent set of data. In Figure 2, a plot is given in galactic coordinates of the distribution of X-ray sources in the sky. I would like to use this plot to indicate the portions of the sky scanned in each flight. In the flight of October 1966 we examined the galactic equator region from $l^{\mathrm{II}} = -15$ to $l^{\mathrm{II}} = +90$ (the region which includes Scorpio and Cygnus). The flight of February 1968, although intended to scan the Cepheus-Lacerta regions, resulted in a fast scan including $l^{\mathrm{II}} = 150$ to $l^{\mathrm{II}} = 190$ and $l^{\mathrm{II}} = 250$ to $l^{\mathrm{II}} = 270$ over the regions of the Crab and Vela. A recent flight in December 1968 included the scan of the region of Cepheus, Lacerta (containing Cas A and Tyco supernovae) from $l^{\mathrm{II}} = 100$ to $l^{\mathrm{II}} = 140$ and extended to $l^{\mathrm{II}} = 190$. In this manner we have examined most of the galactic equator regions visible from White Sands, New Mexico, from $l^{\mathrm{II}} = -15$ to about $l^{\mathrm{II}} = +270°$.

The results of the flight prior to December 1968 have been reported in detail in a series of articles which have appeared in the literature: Giacconi *et al.* (1967a, b), Gorenstein *et al.* (1967), and Gursky *et al.* (1967, 1968). I would like to restrict my remarks in this paper to aspects of those earlier publications which, together with the results of our most recent flight, have a bearing on (1) the X-ray emission from supernova remnants, and (2) the distribution of X-ray sources in the galaxy.

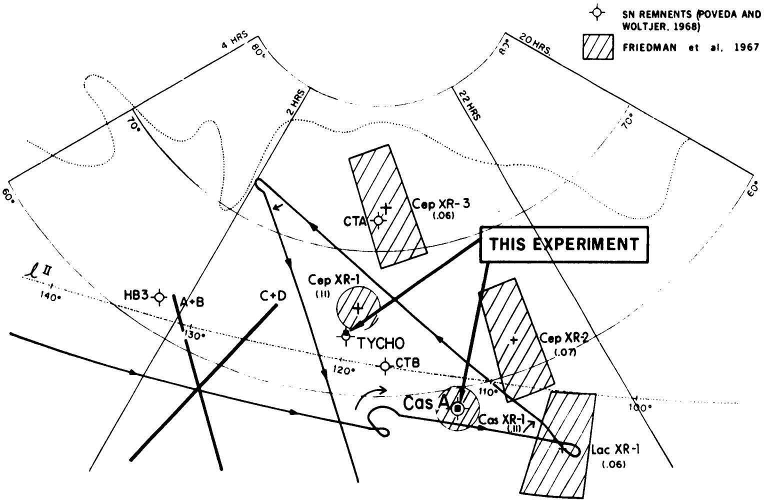

Fig. 3. Motion of the center of the field of view (fov) on the celestial sphere for the Cassiopeia portion of the flight. At earlier times the center moves approximately along the galactic equator starting at $l^{\mathrm{II}} \approx 200°$. The line segments labelled $(A + B)$ and $(C + D)$ show the orientation of the fov and are drawn smaller than the actual fov which is $2° \times 45°$. The numbers along the scan line correspond in time to those in Figure 2. The locations of the X-ray sources observed in this experiment as well as sources reported from a previous survey (Friedman *et al.*, 1967) with their strength relative to the Crab (plus known supernova remnants) are shown.

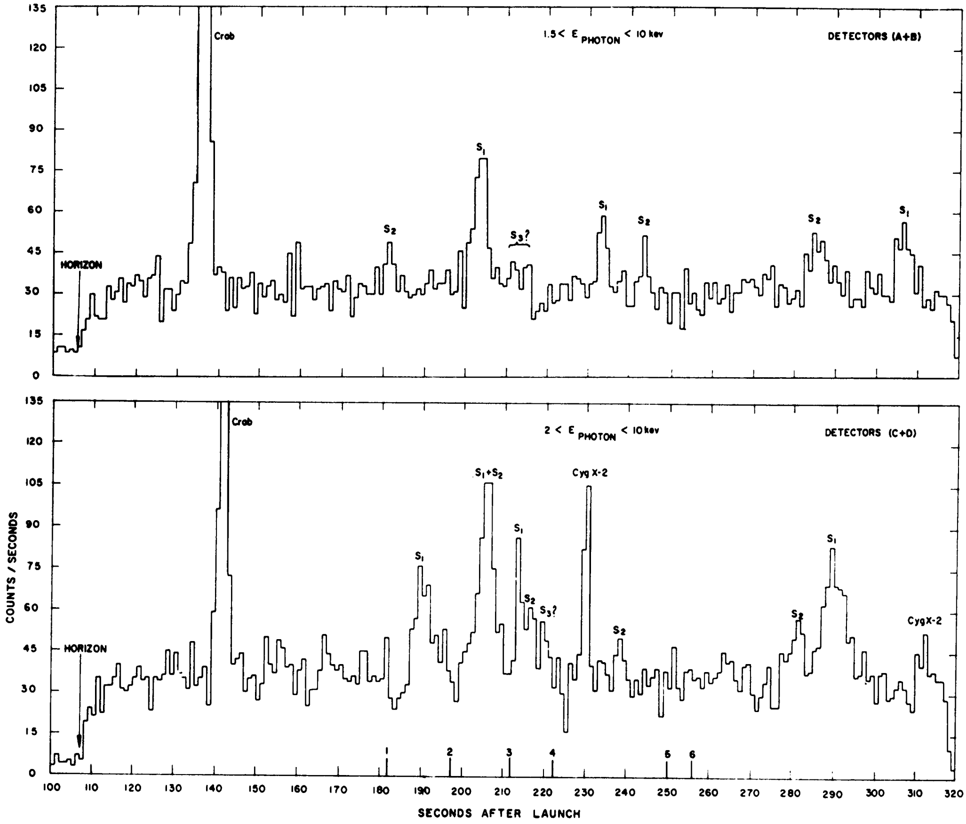

Fig. 4. Actual counts per one second interval vs. time. All the peaks labelled 'S_1' ('S_2') are due to the same source. The numbers along the time scale correspond in celestial position to those of Figure 1. The width of a peak is determined by the instantaneous rate of scan which is either 3°/sec, 1°/sec, or 0.5°/sec.

(1) *Supernovae X-Ray Emission*

In the recent flight of December 1968 we scanned the region of the sky from Crab to Cepheus Lacertae along the galactic equator. The results of this flight, giving greater detail, will shortly by submitted for publication by our group. Briefly the scan mode is shown in Figure 3. The scan was carried out essentially along the galactic equator from $l^{\text{II}} \sim 200–120°$. Complex maneuvers were then carried out to sweep the region containing five previously reported sources: Cep XR-1, XR-2, and XR-3; Cas XR-1 and Lac XR-1 (Friedman *et al.*, 1967).

In Figure 4 the counting rate is shown vs. time. Several obvious peaks in the distribution are observed; in addition, several significant peaks not yet analyzed may also be present. Upon analysis of the aspect photography, all of the obvious peaks except Crab were found to define the position of only two sources corresponding in position to the location of the two supernova remnants Tyco and Cas A. In Figures 5 and 6 the X-ray positions and associated region of uncertainty are shown super-

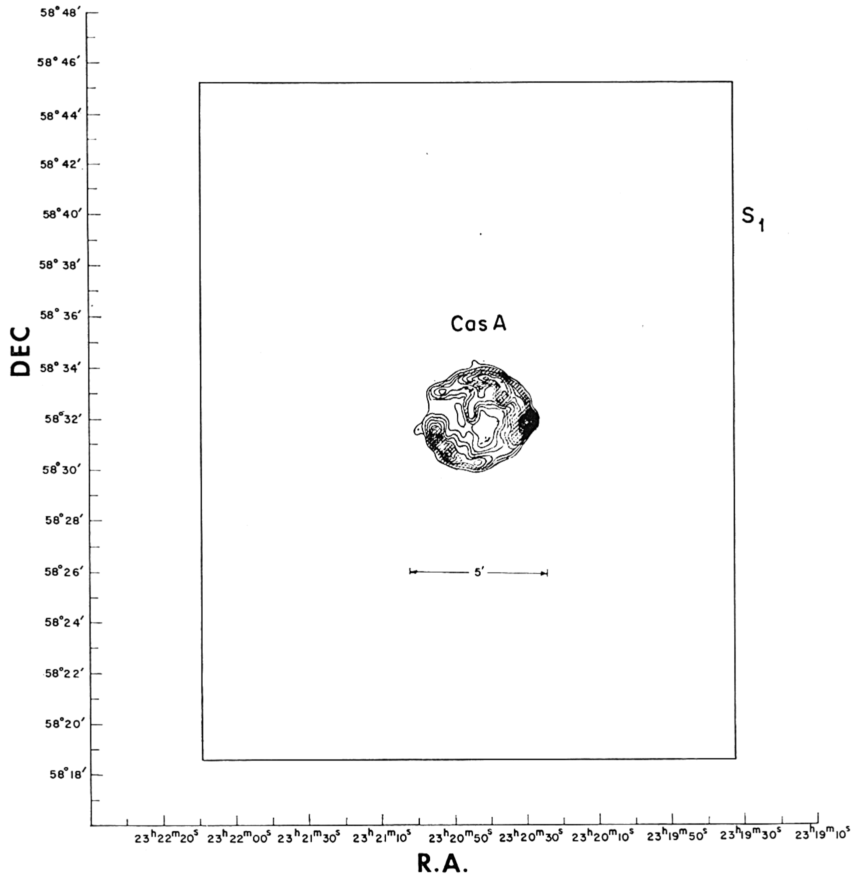

Fig. 5. Position of source S_1 as determined from 'best' intersection of 8 great circle segments. The box shows the region corresponding to a one standard deviation uncertainty in the source position. A radio contour map of Cas A (Ryle *et al.*, 1965) is superimposed upon the position of S_1.

imposed on a radio contour map of the supernova remnants. Although Cep XR-2 and Cep XR-3 were reported to have a strength as large as $\frac{1}{2}$ of that of Cep XR-1 and Cas XR-1, we see at first glance no evidence of their existence. Further detailed analysis may reveal additional sources, but none can be much brighter than $\frac{1}{4}$ of Cas A and Tyco. In particular, we find no evidence for the source Cep XR-3 whose closeness to the location of the supernova remnant CTA-1 had suggested the possibility of an identification with that supernova. Its distance was estimated by Poveda and Woltjer to be about 2000 pc, spectral index $\alpha = 0.2$, a diameter of 120′. On the other hand, we believe that our data confirm very convincingly the emission of X-ray radiation from Cas A and firmly establish the existence of X-ray emission from Tyco SN.

Crab, Tyco and Cas A have thus been established to be X-ray emitters. Kepler SN, CTA-1, and Vela X have been shown not to be X-ray emitters at the present level of sensitivity. While the greater distance from us of Kepler SN (1000 pc) leads us to expect a factor 10 smaller emission from Kepler than from Tyco (3500 pc), CTA-1 and Vela X are estimated to be closer to us than either Tyco or Cas A.

We note that only supernova remnants with an angular diameter less than several minutes of arc have been definitely observed to be X-ray sources. If the diameter is taken to be an indication of the age of the remnant, one would be tempted to conclude that only young supernova remnants are known to be X-ray emitters. On the other hand, the angular diameter may be determined by physical conditions in the interstellar medium surrounding the source or by specific characteristics of the supernova event itself, and not by age.

In any case, it is interesting to note that while other parameters, such as flux density or spectral index of the radio emission, do not correlate with X-ray fluxes, surface brightness in radio and diameter of the remnants (quantities which are not, of course, independent) seem to show a direct correspondence. Roughly the X-ray emission seems to be inversely proportional to some power of the diameter.

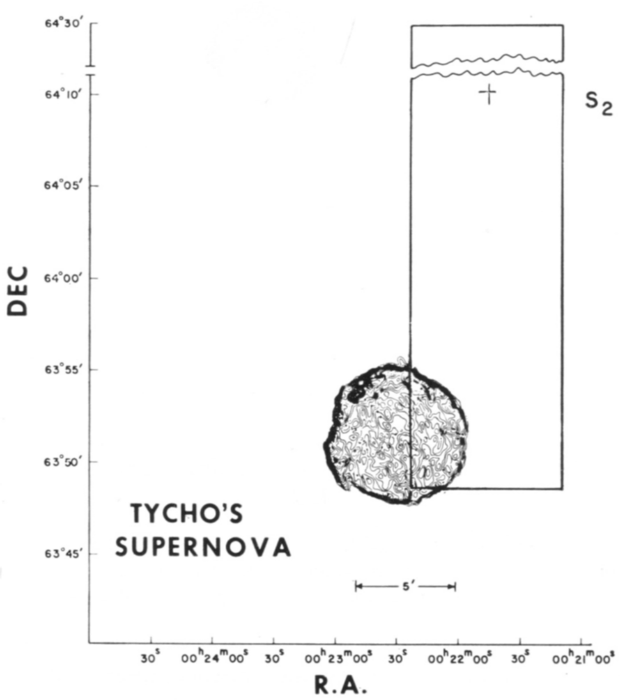

Fig. 6. Position of source S_2 as determined from the 'best' intersection of 6 great circle segments. The box shows the region corresponding to the one standard deviation uncertainty in the source position and the cross indicates the center of the box. A radio contour map of SN1572 (Baldwin, 1967) is superimposed on the position of S_2.

It follows that not all supernova remnants can be assumed to be X-ray emitters, as it has often been done on the basis of coarser surveys (Poveda and Woltjer, 1968). In addition, we note that several of the galactic X-ray sources do not coincide with known supernova remnants. It appears, therefore, unlikely that X-ray emission from supernova remnants can be assumed to be the source of the bulk of the known galactic X-ray objects.

(2) *Galactic Distribution of X-Ray Sources*

As a result of previous surveys, we had adopted as a working hypothesis in a previous paper (Gursky *et al.*, 1967) the point of view that X-ray sources were associated with the galactic spiral arm. Assuming all sources to be of the same intrinsic luminosity, it appeared possible to obtain a consistent picture by assuming that sources with l^{II} between $-15°$ to $+17°$ lie in the Sagittarius arm and the ones with l^{II} between $+36°$ to $+80°$ corresponded to tangential directions of several arms. Figure 7 shows the degree of correspondence which appeared to exist between X-ray source directions and galactic spiral arms structures in neutral hydrogen as determined from the 21 cm radio studies of Sharpless (1965). The Cep-Lac sources were the ones observed by Friedman *et al.* (1967).

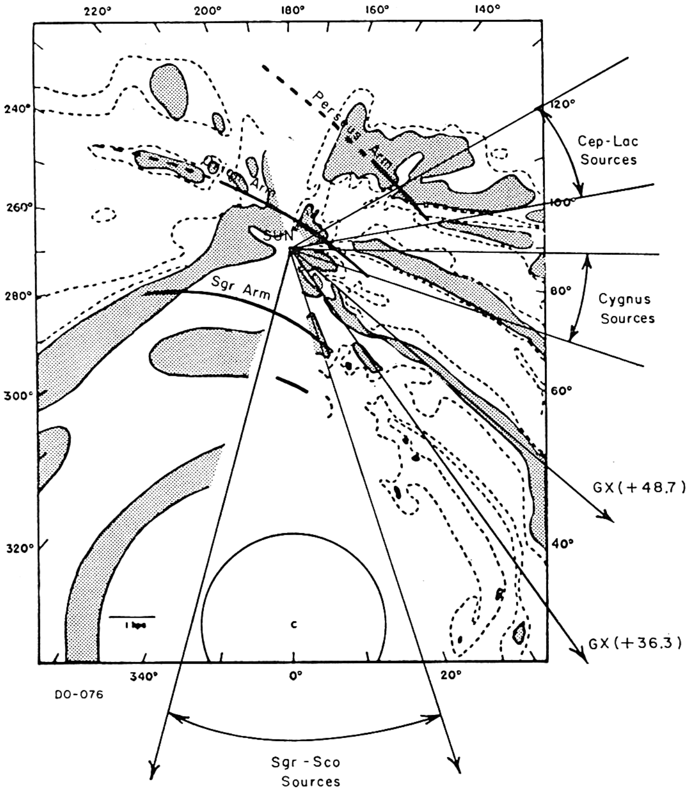

Fig. 7. Direction of X-ray sources superimposed on a map of the galaxy prepared by Sharpless (1965). The map shows the isodensity contours of neutral hydrogen as derived from the 21 cm radio studies and the spiral arms (shown as curved segments of solid and dashed lines) as deduced from optical data. The names used for the arms (Sgr., Orion, and Perseus) are those given by Sharpless.

The fact that except fot the two supernova remnants described above, we observe in the most recent survey no additional sources in the Cep-Lac region makes the validity of our working hypothesis very doubtful. Sources in the Cep-Lac arm would have to be X-ray emitters with intrinsic luminosity less than 0.025 of Crab in order not to be observed.

Also, detailed examination of the spectra of several X-ray sources in the Cygnus and Scorpio-Sagittarius region shows evidence of detectable amounts of absorption at about 1–2 keV energies. The most noticeable effect was observed in Cyg X-3 by Gorenstein *et al.* (1967) and the data are shown in Figure 8. We note that also sources in the direction of Scorpio-Sagittarius show varying degrees of absorption. Assuming this absorption not to occur at the source, but in interstellar space, as indicated by the apparent correlation between visible light obscuration and X-ray absorption, we had noted that the distances we would derive were between 3 and 4 kpc. In view of the uncertainty both in the experimental data and in our knowledge of the absorption properties of the interstellar medium, we had felt this was not in contradiction to our simple model.

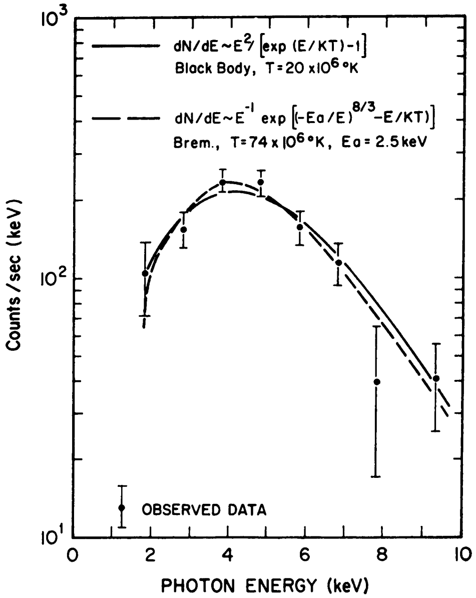

Fig. 8. For the source Cyg X-3 the observed histograms of counting rate vs. energy are compared to the calculated counter response to two assumed photon distributions: (1) $\mathrm{d}n/\mathrm{d}E \sim (Ea/E)^{8/3}$ exp $(-E/KT)/E$, (2) $\mathrm{d}N/\mathrm{d}E \sim E^2/(\exp(-E/KT)-1)$. The parameters Ea and T represent the best fit. Both spectra fit the data about equally well.

We now feel that a more consistent interpretation of the data might be that the sources in the Scorpio-Sagittarius region are, in fact, not associated with the nearby Sagittarius arm, but more distant from us and closer to the galactic center. I understand that Prof. Livio Gratton will discuss the distribution of galactic X-ray sources and compare it to population types of other objects in more detail as part of this symposium. I would only like to note here that the preceding considerations have important consequences both in the prediction of the total X-ray luminosity of our galaxy and in the age of the objects involved.

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