IMPLICATIONS OF RESULTS FROM THE EINSTEIN OBSERVATORY FOR THE X-RAY BACKGROUND

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I. INTRODUCTION

The origin of the diffuse background has been an important question in X-ray astronomy starting from the earliest measurements (Giacconi, et al. 1962). When it was recognized that the X-ray background above 2 keV was isotropic and hence extragalactic (c.f. Schwartz 1970, 1979), it became evident that understanding its origin would have cosmological implications (c.f. Hoyle 1963, Rees 1973). Two general explanations representing opposite points of view have received the most attention. One is that the background is composed of faint unresolved objects which are of the same classes as, but perhaps in earlier phases than, the objects which can be detected directly and identified. If this explanation is correct, then the luminosities and/or proper densities of the objects must be larger at earlier times in the universe, and the magnitude and graininess of the background can be used to place important constraints upon the evolution of the objects. The other is that the background is truly diffuse. The most probable explanation of this type is a hot plasma that pervades the intergalactic medium. If it accounted for only 10% of the background, the mass that could be attributed to such a plasma would represent more matter in the universe than has been detected so far by all other means. Such a large mass would be important dynamically, and in determining the deceleration parameter, although it would not "close" the universe. Furthermore, the density of such a plasma would place constraints upon determining the epoch of galaxy formation.

II. EINSTEIN OBSERVATORY MEASUREMENTS

The differences between the Einstein Observatory and all preceding X-ray astronomy satellites are its ability to detect sources several hundred times fainter and to obtain positions with extremely fine precision. This represents a significant qualitative as well as large quantitative improvement upon previous investigations of the background because the sensitivity and resolution of the Einstein Observatory

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permit us to resolve and study sources which are 10^4 more numerous per unit solid angle and to obtain their optical counterparts. Previous work on the source counts was based upon the interpretation of relatively small fluctuations among fields of several square degrees. With the Einstein Observatory, we are in position to resolve a significant part of the background into identifiable sources.

Two lines of investigation of the Einstein Observatory converge in their conclusions on the origin of the background. The first is the study of the X-ray luminosity of quasars (Tananbaum, et al. 1979), which was described earlier in this Joint Discussion by Henry and Ku. The conclusion of the Einstein quasar investigation is that it is possible to account for essentially all of the X-ray background with QSO's if we assume that their ratio of X-ray luminosity to optical luminosity, L_x/L_{opt}, is like that of the Einstein quasar sample. Although this result is very suggestive, the quasar study by itself is not conclusive. Because of the large spread in the ratio L_x/L_{opt}, there are systematic uncertainties in determining its effective value even for the objects studied. Given that quasars evolve optically, it is hard to imagine that L_x also changes in the precise manner to keep L_x/L_{opt} constant as a function of cosmic time. The uncertainty is compounded by assuming that the value of L_x/L_{opt} for the Einstein quasar sample, which is predominantly radio selected, is applicable to QSO's in general. Also, there are real uncertainties in the density of QSO's, particularly those fainter than 19th magnitude, so that even with the correct effective value for L_x/L_{opt}, it is difficult to make a precise prediction of their integrated contribution to the X-ray background. Finally, we must assume that the X-ray spectra of QSO's (or any other objects for that matter) have the composite spectral shape $dN/dE \propto E^{-1.4}$ (Schwartz 1979) necessary to match the 2 - 20 keV background (c.f. Cavaliere, et al. 1979).

The other line of investigation of the Einstein Observatory that is relevant to understanding the X-ray background is the "Deep Survey" directed by Giacconi (Giacconi, et al. 1979). Because the sensitivity and angular resolution are so much superior to previous surveys (several hundred times better), we are in a regime where, *a priori*, a significant part of the background could be resolved into its possible discrete source components. On the other hand, because of the nature of focusing optics, the nominal energy band is 1 - 3 keV which is below the 2 - 20 keV regime where the extragalactic component is known to be predominant. (Because the energy resolution of the Einstein detectors is finite, there is a non-negligible contribution from even lower energies.) Therefore, the galactic contribution both in terms of discrete sources and diffuse emission may be very important, and we do not necessarily expect that all, or even most, of the actual X-ray background in the Einstein detectors is due to the discrete extragalactic sources which may account for the 2 - 20 keV background. Nevertheless, by detecting and identifying discrete sources, we can determine if extragalactic sources are appearing in Einstein fields at a rate that is consistent with a discrete source hypothesis for the 2 - 20 keV background. If the sources are QSO's and their L_x/L_{opt} is consistent with the Einstein quasar study, then the explanation for the background would be nearly settled. The methodology of the Deep Survey is unique because the optical counterparts are so faint. Unlike the Uhuru, Ariel V, and other wide surveys where most of the optical/radio counterparts were bright and already catalogued, each optical and radio candidates has to be studied individually in order to classify it. The optical and radio work must go in parallel with the X-ray studies and in many respects is more difficult.

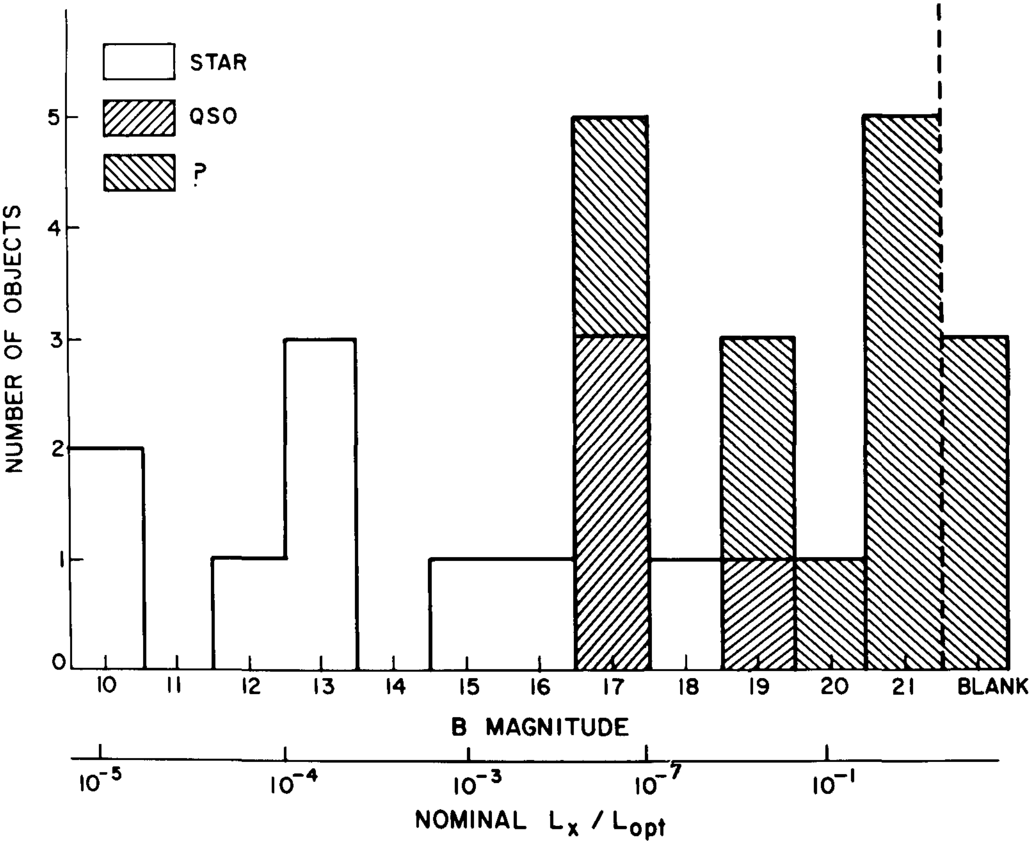

Figure 1. Histogram of number of objects vs. B magnitude for 26 objects found in Deep Survey with good positions. Candidate is the brightest object in the error box (Gursky, private communication). The "Nominal L_x/L_{opt}" scale is obtained by assuming that all of the sources have the same value of $F_x \approx 3 \times 10^{-14}$ erg/cm^2-sec (1 - 3 keV) which is correct within statistical errors except for a few objects.

For present purposes, the most important objective is to eliminate the galactic sources or stars from the sample. If it can be established that the remaning objects are extragalactic, then one can determine their density at the limiting sensitivity of the two Deep Survey fields (2.6 and 3.9) x 10^{-14} ergs/cm^2 sec (1 - 3 keV).* The source density at this intensity provides a second point along with one that is well established by the Uhuru and Ariel V surveys at an intensity of $\sim$1.7 x 10^{-11} ergs/cm^2 sec (2 - 6 keV).

The study of the objects in the Deep Survey field involved the efforts of optical and radio astronomers at the Leiden Observatory and the Hale Observatory, as well as at the Center for Astrophysics. We describe a line of arguments that paraphrases that of Giacconi, et al. and arrives at the same conclusion. Figure 1 is a histogram of the number of objects versus B magnitude for 26 out of the 42 X-ray sources found in the Deep Survey as summarized by Gursky. The 26 objects are those with good positions ($\sim$10 arcsec) because they were seen with the high resolution detector. The tentative optical identification is made with the brightest object in the X-ray error box. Since most of these objects are just above the detection threshold, their X-ray intensities are all similar. Most are within a factor of two of the mean. Therefore, a histogram of the average L_x/L_{opt} for each value of B mag vs. B mag would look quite similar and such a scale is added to Figure 1. Three categories are shown: stars (9), QSO's (4), and a third group (13) of faint objects which are difficult to identify.

The third group is the largest category, and we examine the evidence on whether they are extragalactic. The overall distribution is clearly bi-modal. Stars appear at the lower magnitudes while QSO's and the unidentified objects are dimmer. The range of L_x/L_{opt} for the objects identified as stars in the B mag range 10 to 16 is 10^{-3} to 10^{-5}, which is in good agreement with the value of L_x/L_{opt} for the early to middle main sequence objects that are being detected in the stellar survey (Vaiana, et al. 1979). On the other hand, the unidentified objects are typically B mag $\simeq$ 17 to >21, which is equivalent for the average object to $L_x/L_{opt} = 10^{-2}$ to >0.25. These values are typical of those seen by Tananbaum, et al. in their quasar study. (It should be noted that if 3C273 were removed to a distance where it appeared as intense as the typical Einstein Deep Survey source, it would be too faint optically to identify.) They also happen to be consistent with L_x/L_{opt} for late type M dwarf (main sequence) stars and white dwarfs.

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*These numbers are about 1.5 times larger when they are transformed to the 2 - 6 keV band using the known spectral function for the X-ray background $dN/dE = 7.7E^{-1.4}$ph/cm^2-sec-keV ster.

There are arguments against associating the bulk of these objects with dwarf stars. Dwarf stars are relatively close. In a few cases, the absence of proper motion can be established. This places a lower limit upon their intrinsic X-ray luminosity which is higher than the M stars or white dwarfs seen in the stellar survey. Collectively, the X-ray spectrum of these objects is not as soft as that of M dwarf stars (or white dwarfs) in their normal, i.e. non-flare state. Since they are not observed to flare at the time of the observation, their spectra must resemble the quasars much more than the M stars. The conclusion is that most of the 13 unidentified sources in our sample are likely to be QSO's because their values of L_x, L_x/L_{opt}, and spectral characteristics are in the ranges by the Einstein quasar study. Therefore, most of the 26 sources in our sample are probably extragalactic.

Figure 2 shows the log N(> S) vs. log S curve for extragalactic X-ray point sources. We have two measurements: one at 2.6×10^{-14} erg/cm^{2}s (1 - 3 keV) due to 10 objects which Giacconi, et al. (1979) select as extragalactic, and the other at 1.1×10^{-11} erg/cm^{2}s (1 - 3 keV) from both the Uhuru and Ariel V source count and fluctuation measurements (c.f. Schwartz 1979). The Uhuru measurement is the estimate due solely to the Seyfert luminosity function $\frac{dN}{dL} = 2.5 \times 10^{-7} L^{-2.3}$ Seyferts Mpc^{-3} $(10^{44}$ ergs/s$)^{-1}$ (Tananbaum, et al. 1978), with the upper limit including all the unidentified sources, but excluding the clusters. For the given Seyfert luminosity function, assumed to be valid from 10^{42} to 3×10^{44} ergs/s (2 - 6 keV), we may predict the log N vs. log S curve from Seyferts alone down to very faint S. This is shown as the dashed curve in Figure 2.

Because this curve is not consistent with the Einstein source count measurement, (it falls below it), we have proved that extragalactic sources must evolve with redshift. The demonstration of evolution is the key experimental result which allows discrete sources to provide enough emissivity for the diffuse X-ray background. The general equation for $q_0 = 0$ is

$$\frac{dN}{dS} = (1 + z)^{-3/2(\alpha + 5/3)} f(z) \left(\frac{dN}{dS}\right)_E \quad \text{, where}$$

α is the index of the power law energy spectrum, f(z) is an arbitrary density evolution factor, and $\left(\frac{dN}{dS}\right)_E \equiv K\, S^{-5/2}$.

Figure 2 shows two cases of the general model

$$f(z) = e^{A\tau} = e^{A\, z/(1 + z)} \quad \text{where } \tau \text{ is the fractional}$$

age of the universe at redshift z. In each case we normalize $N(> S) = \int_S^\infty \frac{dN}{dS} dS = 6.3 \times 10^4$ at $S = 2.6 \times 10^{-14}$ ergs/cm^{2}s (1 - 3 keV),

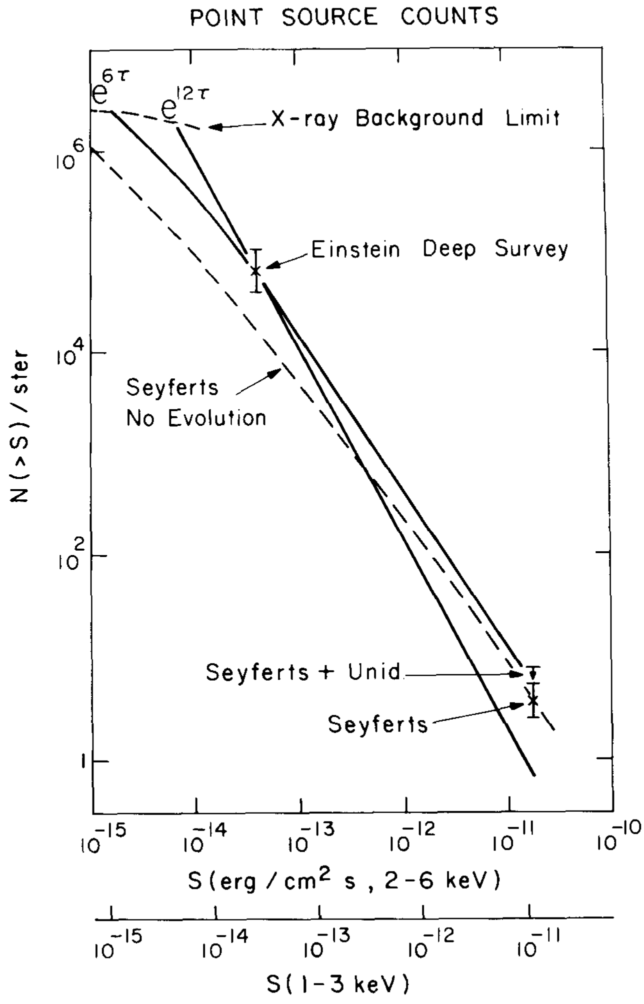

Figure 2. Two points are shown on the N(> S) vs. S curve for extragalactic X-ray sources. One represents Seyfert galaxies found by Ariel V (Elvis, et al. 1978) and Uhuru (Tananbaum, et al. 1978). The addition of unidentified high galactic latitude sources to this sample is shown as an upper limit on extragalactic point sources. The other point is the first result of the Einstein Deep Survey. The dashed curve drawn through the Seyfert point uses the Seyfert luminosity function and assumes no evolution. Two solid curves are drawn through the Einstein Deep Survey point representing two values of a parameter in an evolutionary model that is exponential. The short dashed curve at the upper left indicates where the population of sources must terminate in order to avoid exceeding the X-ray background.

assuming that the observed sources are at a mean $\bar{z} \sim 1$, and then solve for z_{max} at which the sources must cut off to avoid exceeding the diffuse intensity

$$I = \int_{S\,(z_{max})}^{\infty} S\frac{dN}{dS}\,dS = 2 \times 10^{-8} \text{ergs/cm}^2\text{s ster } (1 - 3 \text{ keV}).$$

The model with A = 6 is very interesting in view of the above discussion that the deep survey sources are QSO's. With a small normalization error, we see that the log N vs. log S curve in this case smoothly merges with that due to Seyferts, and would give strong evidence of the continuity of these objects, if verified. The model with A = 12 would be more appropriate for recent estimates of the evolution of radio steep or optically selected quasars (Schmidt 1979). As shown, the sources cut off at $z = 1.9$, but within the errors they are consistent with an extension to $z = 3$.

III. CONCLUSIONS

The final result is that the Einstein Deep Survey and quasar investigations converge to the conclusion that the X-ray background is composed principally of unresolved sources and that they are probably QSO's. According to Giacconi et al. (1979) sources of the type seen in the Deep Survey themselves account for about 37% of the background. Assuming QSO evolution models as suggested by optical observations, the remainder of the background could easily be accounted for. This apparently leaves little room to observe a possible residual intergalactic source of X-rays that is truly diffuse. However, uncertainties in the X-ray flux and spectrum of QSO's and their evolution will probably always make it impossible to exclude a contribution of up to about 10% from an intergalactic plasma, and an even larger contribution cannot be rigorously excluded at the present time. Yet the existence of such a plasma at a level that produces only a small fraction of the X-ray background would still represent more mass than has been found previously in the universe. How could one detect such a plasma if it is not possible to observe it directly in face of the overwhelming contribution by the unresolved QSO's? The answer may lie in another topic of investigation of the Einstein Observatory, the study of the X-ray structure of clusters of galaxies. The spatial distribution of hot gas near the outer boundaries of a cluster of galaxies may be affected by the pressure exerted by a gas in the intergalactic medium that may be even hotter (c.f. Cavaliere and Fusco-Femiano 1978, Kinzer, et al. 1978). External pressure will be manifested in subtle but possibly detectable effects upon the shape of the X-ray surface brightness distribution. Certainly more theoretical work would be needed to help interpret such effects if they are indeed observed.

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