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STAR-FORMING GALAXIES AND THE X-RAY BACKGROUND

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ABSTRACT

We propose that star-forming galaxies are a major, perhaps dominant, component of the X-ray background ($\sim$2–10 keV). Such star-forming galaxies may be largely powered by superluminous Population I massive X-ray binaries (MXRB), formed in the wake of star formation in regions of low metallicity. MXRB have very hard X-ray spectra (2–30 keV) thus matching the overall spectrum of the XRB extremely well after subtraction of the contribution from Seyferts and quasars and allowing for redshifts of the star-forming galaxies up to at least ~ 1.

Star-forming galaxies at moderate redshift and with moderate numbers (100–1000) of MXRB may evolve into the infrared galaxies found at low redshifts using *IRAS*, and may also be closely related to those galaxies identified with sub-mJy radio sources. We find that the relationship between X-ray and infrared luminosities for starburst/peculiar galaxies and *IRAS* galaxies is indistinguishable. Using this correlation to convert the *IRAS* galaxy luminosity function to an X-ray luminosity function, we estimate a contribution to the XRB at 2 keV in the range 20%–30% with moderate evolution, rising to at least 50% with evolution similar to that of active galactic nuclei (AGN). In the energy range $\sim$2–10 keV, star-forming galaxies at intermediate redshifts may dominate the XRB. We also predict the X-ray number counts of star-forming galaxies, showing that one needs to reach very low fluxes $\sim 10^{-15}$–10^{-16} ergs cm^{-2} s^{-1} to quantify directly any X-ray evolution.

Subject headings: galaxies: stellar content — galaxies: X-rays — infrared: sources — stars: formation —
X-rays: sources

I. INTRODUCTION

From the results of the *Einstein* deep surveys, it has been established observationally that at least $\sim$30% of the all-sky, X-ray background (XRB) in the energy range 1–3 keV comes from AGN at redshifts in the range 0.4–1.2 (Griffiths *et al.* 1983, 1988). However, analysis of spatial fluctuations in the *Einstein* Deep Survey counts (Hamilton and Helfand 1987; Barcons and Fabian 1990) has indicated the possible presence of a relatively smooth component of the XRB with a corresponding surface density of discrete sources of at least several thousand per square degree, possibly galaxies. The X-ray log $(N > S)$/log (S) curve (Fig. 1) would then be dominated at the faint end by these galaxies, which would first appear as a minority amongst the discrete sources detected in the *Einstein* Deep Surveys (Griffiths *et al.* 1990) and possibly the Medium-Sensitivity Survey. The nature of such galaxies is the subject of this paper.

The thick solid line in Figure 1 labeled Medium-Sensitivity Survey is from Gioia *et al.* (1990), and connects the early sky-survey results from *Uhuru*, *Ariel V*, and *HEAO-1* with the original *Einstein* Deep Survey point of Giacconi *et al.* (1979). The AGN component of the Medium-Sensitivity Survey is also shown, with a slope of -1.7. The original work in the Pavo field is labeled GR83 (Griffiths *et al.* 1983), dominated by AGN in the redshift range 0.4–1.2. The reanalyzed Pavo images resulted in the data point labeled GR88 (Griffiths *et al.* 1988), dominated by sources detected with the high resolution imager and identified with AGN and candidate AGN of optical magnitude 20–21. The dashed curve with slope -1.2 (AGN?) is consistent with the deep survey counts and with the fluctuation analysis of Hamilton and Helfand (1987), as well as with the equivalent slope of optical quasar counts (the upper abscissa shows the average blue magnitude of AGN corresponding to the X-ray fluxes on the lower abscissa).

The solid line at upper left (following Giacconi and Zamorani 1987) shows the number of sources needed at any flux limit to explain the whole of the XRB at 2 keV, on the assumption of extrapolation of the 3–20 keV spectrum to lower energies ($kT = 40$ keV). If, as indicated by the *HEAO* A-2 experiment, and by the overall IPC counts (Wu *et al.* 1989), the XRB spectrum turns up below 3 keV, then the upper left line is a lower limit (indicated by arrows) and should be raised by $\sim$30%.

A significant diffuse component of the XRB (indicated at top left) has not been ruled out by the *Einstein* observatory or by all-sky fluctuations of the XRB. A major component is rendered unlikely however, by consideration of the XRB spectrum after subtraction of known source classes, and has been limited to $\sim$3% by results from the *Cosmic Background Explorer*, *COBE* (Mather *et al.* 1990).

Given the problems with an AGN interpretation of the whole of the XRB (see Fabian *et al.* 1990 and references therein), we consider here an alternative or additional source, especially in the 3–20 keV energy range above that of the Einstein observatory, viz. the integrated X-ray emission from an early population of low-metallicity, massive X-ray binaries (MXRB) in star-forming galaxies (Griffiths 1989), especially in galaxies at the limit of the present deep-optical, radio, and infrared surveys (e.g., Tyson 1988; Windhorst *et al.* 1985). MXRB are likely to be found in greatest numbers in active star-forming galaxies, a galaxy population observed easily in the far-infrared. We therefore draw upon the combined observational data set of *IRAS* and *Einstein* to evaluate the relationship between X-ray and infrared luminosity of star-forming galaxies, and then use the appropriate luminosity function from *IRAS* data in order to calculate the contribution of such galaxies to the XRB.

In § II we review the properties of the X-ray binaries which may be responsible for the bulk of the X-ray emission from star-forming galaxies, and in § III we make detailed calculations of the contribution of the star-forming galaxies to the X-ray background, based on the observed correlations between X-ray and infrared emission, and we also predict their X-ray counts (throughout this paper, the values $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$ have been used, unless otherwise stated). In § IV we comment briefly on the importance of metallicity at intermediate epochs, and in § V we show how the redshifted MXRB spectra can match that of the XRB. Our conclusions and predictions are presented in §§ VI and VII, respectively.

II. POPULATION I MXRB IN LOW-METALLICITY SYSTEMS

The Population I X-ray binaries were established as a class of X-ray emitters in the late 1960s and 1970s (for a summary of their X-ray properties see Rappaport and Joss 1983). MXRB have primaries of $\sim 20\ M_\odot$, with accreting secondaries of 1–7 $M_\odot$. Their orbital periods are typically a few days, and their optical properties have been summarized by van Paradijs (1983). They start emitting X-rays $\sim 10^7$ years after the formation fo the initial massive binary, and the epoch of X-ray emission is rather uncertain, but probably lasts for at least 10^5–10^6 yr (see van den Heuvel 1983 for a review of the evolution of such systems). The presently active and known MXRB in our Galaxy number ~ 20 (van den Heuvel 1983) with X-ray luminosities of $\sim 10^{38}$ ergs s^{-1} and typical X-ray temperatures > 15 keV, spectra which make them excellent candidates as contributors to the all-sky background, provided that the low-metallicity counterparts of such systems are sufficiently common in regions of star-formation at moderate redshifts.

Our Galaxy does not contain any low-metallicity MXRB, so that sources like Cyg X-1 and Cen X-3 may be underluminous examples of those to be found in star-forming galaxies. We have to look at least as far as the Local Group, where we find SMC X-1 and LMC X-4. The low metallicity of the SMC has been taken as the reason for the extraordinary X-ray output of the SMC—rivaling the total X-ray output of the Galaxy, with only 1/10 the mass (Clark *et al.* 1978). The O-stars in the SMC are also more luminous in X-rays than O stars in the Galaxy. Generally, low metal content means lower X-ray opacity in the accreting material, driving up the accretion rate and enhancing the production of hard X-rays. The high-energy tail of binaries like SMC X-1 may be especially important in considerations of the XRB.

Nearby galaxies include examples of superluminous sources in M82 (Watson, Stanger, and Griffiths 1984), M101 (Trinchieri, Fabbiano and Romaine 1990), and perhaps NGC 253 (Fabbiano and Trinchieri 1984). Long and Van Speybroeck (1983) drew attention to the compact binaries in "normal" galaxies, where it is not unusual to find individual sources with luminosities in excess of 10^{39} ergs s^{-1}: M101 has four or five such sources, M100 has a source emitting in excess of 10^{40} ergs s^{-1}, and M82 likewise has a source in an outlying arm with $L_x \sim 10^{39}$ ergs s^{-1}, possibly variable (Schaaf *et al.* 1989). Although not individually identified with massive X-ray binaries (note that this can be done with the HST in some cases), we make the plausible assumption here that such sources are members of the class typified by SMC X-1.

The lifetime of X-ray emission is probably enhanced in metal-poor MXRB; the supergiant branch on the Hayashi track is shifted to the blue, and the low metallicity means that core helium burning will occur on the blue side of the Hertzsprung gap; a longer time will be spent there and the accreting wind may also be stronger, driving up the X-ray luminosity.

The X-ray spectra of the MXRB are typically flat in the 2–10 keV range, i.e., they can be characterized by bremsstrahlung temperatures in excess of 10^8 K, or $kT > 15$ keV. Examples are reviewed in Rappaport and Joss (1983) and in Nagase (1989) (see § V). Although individual X-ray spectra have not yet been obtained for star-forming galaxies, Fabbiano (1989) has suggested that the summed spectrum of a few spiral galaxies appears hard over the limited energy range of the *Einstein* imaging proportional counter, consistent with that expected if their emission is dominated by X-ray binaries. We note that the total X-ray binary contribution will generally be a composite of MXRB and low- or intermediate-mass X-ray binaries. Some of the latter objects also have very hard X-ray spectra and high-energy tails. The X-ray spectrum of the starburst galaxy M82 has been reported by Schaaf *et al.* (1989), who combined the data from the *EXOSAT* and *Einstein Observatories* with the result that the composite spectrum has an apparent temperature of $kT \sim 10$ keV, but this is presumably a composite of the soft X-ray component from the outflowing wind (Watson, Stanger, and Griffiths 1984), combined with a hard component from the X-ray binaries. We do not consider the contribution to the soft X-ray background from the outflowing wind here, but concentrate instead on the binary component.

III. INFRARED STAR-FORMING GALAXIES

Young, Kleinmann, and Allen (1988) and Devereux (1989) have presented evidence that infrared starburst galaxies are powered by massive, young stars in heavily obscured H II regions, thus supporting the hypothesis that significant X-ray emission arises from MXRB in such regions of star-forming galaxies.

In this section we estimate the contributon of star-forming galaxies to the X-ray background and predict their X-ray number counts. To achieve this aim, we select an infrared luminosity function for a complete sample of star-forming galaxies, converting it to an X-ray luminosity function using the relationship between X-ray and infrared luminosity.

The term "starburst galaxy" refers to an object in which the star-formation rate is larger than the value which could be maintained in equilibrium over the lifetime of the galaxy. The most efficient indicator of a starburst is now recognized to be the far infrared emission, due to the reradiation from dust heated by young massive stars (e.g., Young, Kleinmann, and Allen 1988). From the optical point of view, starbursts have previously been characterized (e.g., Balzano 1983) by a bright, blue galaxy core which emits a strong, narrow emission line spectrum similar to low-ionization H II region spectra.

Franceschini *et al.* (1988*a*) have derived the 60 μm luminosity function for a sample of starburst/interacting (S/I) galaxies. These were *optically* selected and comprised, in addition to non–Seyfert Markarian galaxies, galaxies classified in the UGC catalog as peculiar, eruptive, disrupted, interacting and blue compact. The luminosity function so derived represents a *lower* limit to the 60 μm luminosity function of starburst galaxies, simply because starburst galaxies are better selected in the infrared. This is well illustrated by the fact that Devereux (1989), using infrared photometry and optical spectroscopy, and comparing the IRAS Point Source Catalog (1985) with the Nearby Galaxies Catalog (Tully 1988), has defined a sample of 20 nearby, high-luminosity, starburst galaxies only five of

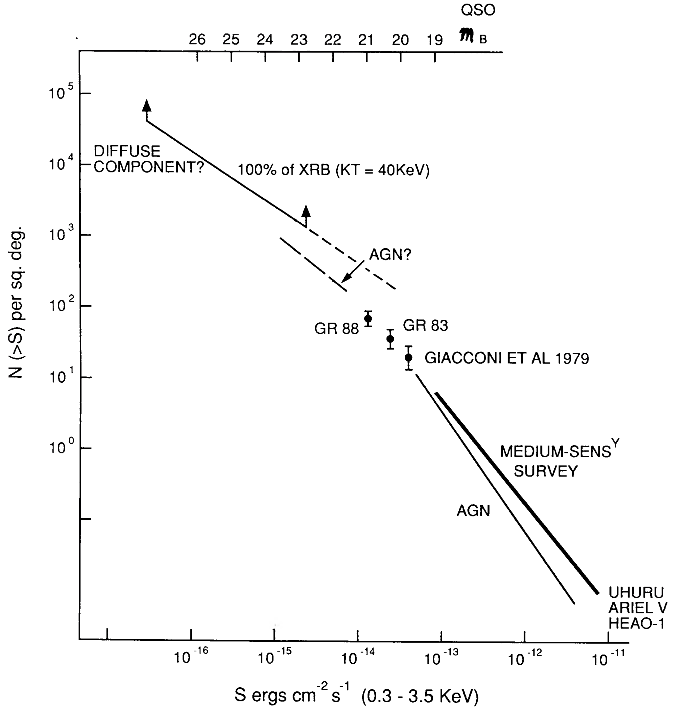

FIG. 1.—The log ($N > S$)-log (S) for extragalactic X-ray sources

which were included in the compilation of Balzano (1983), which relied mostly on optical data.

The *IRAS* bright galaxy luminosity function (Soifer *et al.* 1987), on the other hand, should be more representative of the star-forming galaxy phenomenon, although it includes a minority of Seyfert and normal galaxies. It was derived from a complete sample of 324 objects with 60 μm flux densities greater than 5.4 Jy selected from the *IRAS* catalogs. This sample is more infrared active than optically selected galaxy samples.

In the following we will then use both luminosity functions for our calculations, keeping in mind that the "true" luminosity function of star-forming galaxies lies in between the two, and is probably best represented by the *IRAS* bright galaxy luminosity function.

a) The X-Ray/Infrared Luminosity Relationship

The relationship between X-ray and infrared luminosities was derived for both *IRAS* and S/I galaxies. X-ray data, in the 0.5–3.0 keV energy range, were found for 26 *IRAS* galaxies: 18 objects were in the sample of normal galaxies of Fabbiano, Gioia, and Trinchieri (1988) while eight more were in the sample of starburst/peculiar galaxies studied by Fabbiano, Feigelson, and Zamorani (1982). Although this represents less than 10% of the whole *IRAS* sample, this subsample covers more than two orders of magnitude in both X-ray and infrared luminosities, with a mean-infrared luminosity only a factor of 3 smaller than that of the *IRAS* sample. Infrared data were available for 23 objects in the starburst/peculiar sample of Fabbiano, Feigelson, and Zamorani (1982), which was used to derive the X-ray/infrared luminosity relationship for S/I galaxies. Distances given in the two references above (which assumed $H_0 = 50$ km s^{-1} Mpc^{-1}) were used to compute the luminosities in the X-ray band and at 60 μm. The presence of some upper limits was properly taken into account by using the Survival Analysis package (Feigelson and Isobe 1988) of the Space Telescope Science Institute Science Data Analysis System (STSDAS). For the *IRAS* sample the best linear fit, using the EM method, was given by

$$\log L_{x(0.5-3.0\ \mathrm{keV})} = (9.69 \pm 5.03) + (0.70 \pm 0.12) \log L_{60\ \mu\mathrm{m}} , \tag{1}$$

while for the S/I sample it was

$$\log L_{x(0.5-3.0\ \mathrm{keV})} = (13.26 \pm 6.12) + (0.62 \pm 0.14) \log L_{60\ \mu\mathrm{m}} . \tag{2}$$

The two correlations are both significant at more than the 99.6% level, as shown by the generalized Kendall's τ test and the Cox's proportional hazard model (Feigelson and Isobe 1988). The significance level does not change using fluxes instead of luminosities.

The two relationships are practically indistinguishable and agree very well within less than 1 σ. This is shown in Figure 2, where we also plot the X-ray versus the infrared luminosity for the two samples. The similarity of the relationships is not due to the fact that the two samples have eight objects in common: the exclusion of those objects from the *IRAS* sample does not affect the correlation. Moreover, the whole sample of 46 normal galaxies of Fabbiano, Gioia, and Trinchieri (1988) shows practically the same relationship between the two variables. The average value of the X-ray to infrared ratio, obtained with the Kaplan-Meier estimator (Feigelson and Isobe 1988), is $\langle \log (L_x/L_{60\ \mu\mathrm{m}}) \rangle = -3.32 \pm 0.10$ for the *IRAS* sample, in very good agreement with that of the S/I sample $\langle \log (L_x/L_{60\ \mu\mathrm{m}}) \rangle = -3.27 \pm 0.11$. Finally, the hypothesis that the two distributions of $\log (L_x/L_{60\ \mu\mathrm{m}})$ were not drawn from the same parent population was rejected employing the logrank, the Gehan's and the Cox-Mantel tests (Feigelson and Isobe 1988), since it was significant only at the 20% level.

We can then infer that *the X-ray to far infrared ratio is similar for IRAS, starburst and normal galaxies*. This is an important new result, although it had been previously noted

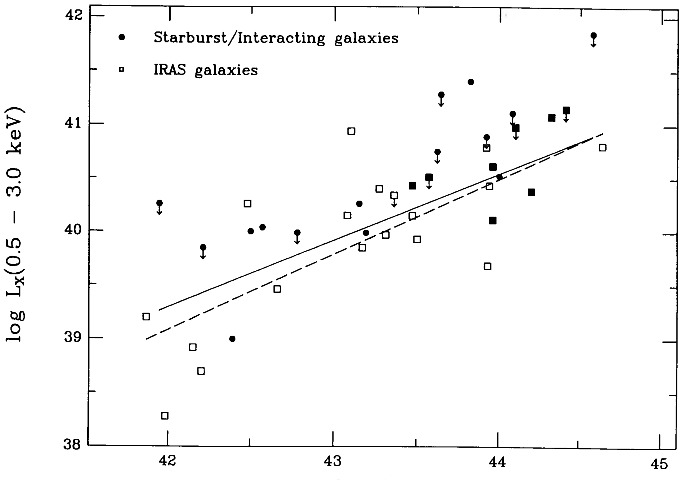

FIG. 2.—The X-ray luminosity in the 0.5–3.0 keV band vs. the infrared luminosity (νL_ν) at 60 μm for starburst/interacting galaxies (*solid points*) and *IRAS* galaxies (*open squares*). The best linear fits for the two samples (S/I: *solid line; IRAS: dashed line*), taking into account the presence of upper limits, are also plotted.

that the far-infrared to radio ratios (Helou, Soifer, and Rowan-Robinson 1985) and X-ray to radio ratios (Fabbiano, Trinchieri, and MacDonald 1984) had similar distributions for starburst and normal galaxies.

b) The X-Ray Luminosity Function

Having established the correlation between X-ray and infrared luminosities, which is independent of the attempt to classify galaxies as actively "starburst" or not, we can use the two infrared luminosity functions and the X-ray/infrared luminosity relationship for S/I galaxies to derive the corresponding X-ray luminosity functions for *IRAS* and S/I galaxies and hence the contributions to the XRB.

It is easy to show that, if $L_x \propto L^{\epsilon}_{60\,\mu\mathrm{m}}$, the differential X-ray luminosity function is $\phi(L_x) = \phi(L_{60\,\mu\mathrm{m}})(L_{60\,\mu\mathrm{m}}/L_x)\epsilon^{-1}$. Our results are shown in Figure 3. The *IRAS* galaxy X-ray luminosity function can be well approximated by a double power law of slope -2.3 below $\log L_x \simeq 40.7$ and slope -4.4 above the break. The S/I galaxy X-ray luminosity function seems to turn over at low luminosities but this is probably due to incompleteness (Franceschini *et al.* 1988*a*). However, the S/I luminosity function can be approximated by a double power law of slope 1.2 below $\log L_x \simeq 39.6$ and slope -2.4 above this luminosity. The number density of *IRAS* galaxies with $\log L_x \geq 39.4$ is $\sim 1.2 \times 10^7$ Gpc^{-3}, while that of S/I galaxies with $\log L_x \geq 39.3$ is $\sim 1.3 \times 10^6$ Gpc^{-3}. The luminosity densities, which enter in the calculations of the XRB, are $\rho(L_{0.5-3.0\,\mathrm{keV}}) \sim 7.7 \times 10^{46}$ ergs s^{-1} Gpc^{-3} and $\rho(L_{0.5-3.0\,\mathrm{keV}}) \sim 1.0 \times 10^{46}$ ergs s^{-1} Gpc^{-3}, respectively, corresponding to $\rho(L_{2\,\mathrm{keV}}) \sim 5.7 \times 10^{46}$ ergs s^{-1} Gpc^{-3} and $\rho(L_{2\,\mathrm{keV}}) \sim 7.6 \times 10^{45}$ ergs s^{-1} Gpc^{-3} ($\alpha_x = 0.3$, see § V). Since the luminosity functions are certainly going to extend to lower luminosities, these values (and the associated XRB contributions) should be regarded as lower limits.

c) The Contribution to the XRB

The intensity of the XRB due to star-forming galaxies can be calculated, for a Friedmann-Robertson-Walker cosmology, from the equation

$$I_x = \frac{c}{4\pi H_0} \iint \frac{L_x \phi(L_x, z) dL_x dz}{(1+z)^{(2+\alpha_x)}(1+2q_0 z)^{1/2}}, \tag{3}$$

where α_x is the X-ray spectral index. Assuming no evolution (i.e., constant luminosity and number conservation) the fraction of the XRB at 2 keV due to objects having $z \leq z_{\max}$ can be expressed as

$$F(2\text{ keV}) \simeq 2.6 \times 10^{-48}\, \rho(L_{2\,\mathrm{keV}})\, \frac{1-(1+z_{\max})^{(-1-\alpha_x-q_0)}}{1+\alpha_x+q_0}, \tag{4}$$

where $\rho(L_{2\,\mathrm{keV}})$ is the luminosity density at 2 keV in units of ergs s^{-1} Gpc^{-3}, and q_0 can be 0 or 0.5. For the case of luminosity evolution of the type $L(z) = L(0) \exp[T(z)/\tau]$, where $T(z)$ is the look-back time, and τ is the time scale of the evolution, equation (3) can be solved numerically.

The form of the evolution of star-forming activity in galaxies is still unsolved. Danese *et al.* (1987) and Condon (1987) have explained the upturn in the sub-mJy radio counts with S/I galaxies evolving in luminosity on time scales of the order of 20%–25% of the Hubble time. Franceschini *et al.* (1988*b*) have shown that the same evolving population (plus nonevolving "normal" galaxies) can explain the deep *IRAS* 60 μm counts. Hacking, Condon, and Houck (1987) and Lonsdale and Hacking (1989), on the other hand, explain the same *IRAS* counts with density or luminosity evolution of *all IRAS* galaxies of the order of $(1+z)^{3-4}$. The latter authors, though, caution that some or all of the excess faint counts could be due to the effects of large scale structures, such as superclusters.

It has also become apparent that nuclear activity may be related to starburst activity (Balzano 1983). Ward (1988) has shown a correlation between X-ray luminosity and Brackett γ emission in starburst nuclei, supporting the hypothesis of X-ray emission arising from MXRB in the nuclear regions. It would not be unreasonable for the evolution of such starburst nuclei to evolve as rapidly as quasars. Some fraction of the active star-forming galaxies at high redshift may evolve into AGN (Norman and Scoville 1988); this may well be the case for the luminous *IRAS* galaxies, and may indeed be a common origin for AGN, but the calculations performed here are for star-forming galaxies in general, whether or not they develop AGN.

Figure 4 shows the fractional contribution of S/I galaxies (curves *a*) and *IRAS* galaxies (curves *b*) to the XRB at 2 keV, as a function of redshift, for the cases of no evolution, $\tau = 0.4$, and $\tau = 0.2$ assuming $\alpha_x = 0.3$ (see § V) and $q_0 = 0$. The value $\tau \sim 0.4$ has been derived from the infrared evolutionary time scale of Franceschini *et al.* (1988*b*), converted to an X-ray time scale through equation (2); this value is also consistent with the luminosity evolution models of Hacking, Condon, and Houck (1987). The value $\tau \sim 0.2$ is typical of the X-ray evolution of AGN (Maccacaro, Gioia, and Stocke 1984).

Star-forming galaxies with moderate evolution contribute then between 4%–26% of the XRB at 2 keV, depending on the choice of the luminosity function: given our previous discussion, higher values are preferred. It is also interesting to note that nonevolving *IRAS* galaxies contribute $\sim 10\%$ of the XRB at 2 keV, while the same objects following a quasar-like evolution would exceed 50% of the background when integrated to $z \sim 1.5$. We remark that these values refer to $\log L_x \gtrsim 39.3$ and should therefore be considered as lower limits:

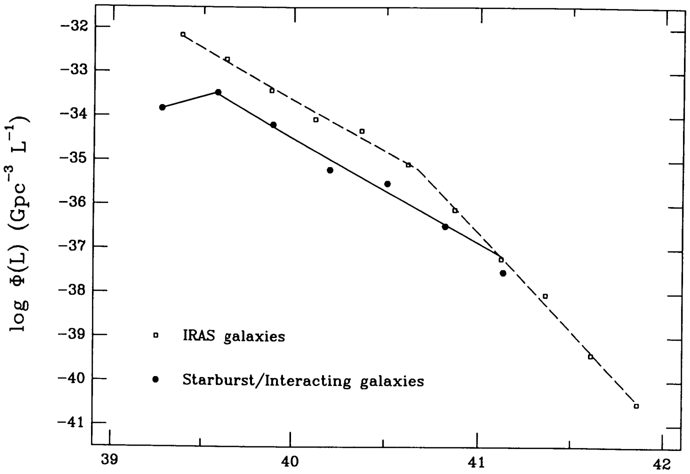

FIG. 3.—The differential X-ray luminosity function for starburst/interacting (*solid points*) and *IRAS* galaxies (*open squares*), converted from the infrared luminosity function through the mean X-ray/infrared relationship. Simple power-law fits are also shown.

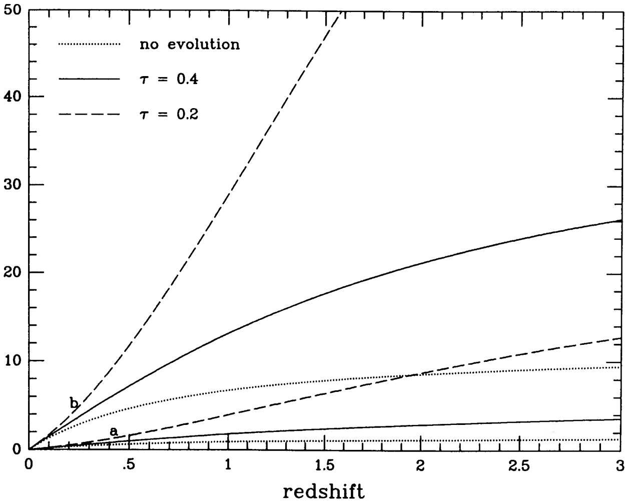

FIG. 4.—Fraction of the 2 keV XRB arising from S/I galaxies (curves *a*) and *IRAS* galaxies (curves *b*) for the cases of: no evolution (*dotted lines*); $\tau = 0.4$ (*solid lines*); $\tau = 0.2$ (*dashed lines*).

for example, an extension of the low end of the *IRAS* luminosity function to a luminosity a factor of 3 smaller would increase our estimate of the contribution to the XRB by ~60%. We note in particular that the evolutionary models of Hacking, Condon, and Houck (1987)—infrared evolution $(1 + z)^{3-4}$ for $q_0 = 0.5$—converted to an X-ray evolution through equation (2), predict a contributon to the 2 keV XRB in the range 22%–34% with $\alpha_x = 0.3$.

Our results agree with the 13% contribution to the XRB from nonevolving *IRAS* galaxies found by Weedman (1986) using early *IRAS* data, based on the average ratio of infrared to X-ray luminosity from the dozen galaxies in Fabbiano, Feigelson, and Zamorani (1982) which were detected in X-rays. The low contribution (5%–11%) found by Danese *et al.* (1987) for evolving starburst galaxies is due to their choice of luminosity function (Franceschini *et al.* 1988*a*), based on an optically selected sample (see previous discussion).

d) *The X-Ray Number Counts*

The expression which relates the differential counts to the luminosity function, assuming a Friedmann-Robertson-Walker cosmology, is

$$\frac{N(S, z)}{4\pi} dS\,dz = 4\pi \frac{c}{H_0} \frac{\phi[L(S, z), z]D_L^4(z)}{(1 + z)^{4-\alpha}(1 + 2q_0 z)^{1/2}} dS\,dz\,, \quad (5)$$

where c is the speed of light, and $D_L(z)$ is the luminosity distance. An integration between the appropriate redshifts gives the differential counts $N(S)$ and the integral counts are $N(>S) = \int N(S)dS$.

In our calculations we used the X-ray luminosity functions previously derived assuming $\alpha_x = 0.3$, and $q_0 = 0$ and carrying out the computation up to a redshift $z_{\max} = 3$. We also assumed comoving number density conservation and three evolutionary cases: no evolution, $\tau = 0.4$, and $\tau = 0.2$.

Our results are shown in Figure 5 for S/I galaxies (curves *a*) and *IRAS* galaxies (curves *b*). Star-forming galaxies may reach a peak in the integral counts at 10^{-16}–10^{-19} ergs cm^{-2} s^{-1}, with sufficient numbers in the range 5–10 × 10^{-15} ergs cm^{-2} s^{-1} that they start to appear in the *Einstein* Deep Surveys. They should also show up in the *ROSAT* deep surveys as individual detections in slightly larger numbers. Figure 5 also illustrates the difficulty in establishing the X-ray evolution of star-forming galaxies: the evolving and nonevolving cases do not differ significantly until large samples are observed at flux limits of ~10^{-15}–10^{-16} ergs cm^{-2} s^{-1}„ beyond the range of current instruments and barely possible with *AXAF*. Detection in the *Einstein* and *ROSAT* deep surveys is, of course, aided by X-ray selection: small numbers of objects will be detected with unusually large X-ray/infrared luminosity ratios, in a similar fashion to the X-ray selected AGN in the *Einstein* Medium-Sensitivity and Deep Surveys.

Figure 5 also shows the integral counts for the extragalactic population of the Extended Medium Sensitivity-Survey (EMSS) from Gioia *et al.* (1990). There are at least 13 "inactive" galaxies in the EMSS, 20 objects classified as AGN on the basis of their X-ray luminosities and α_{ox} values but with no or narrow emission lines in the 3400–6000 Å spectral region (although at least five of them have a strong Hα) and 67 unidentified extragalactic objects. Thirteen extragalactic objects are also *IRAS* sources: of these, four are Seyfert I galaxies, one is a quasar, four are classified as AGN—but they do not appear in the Catalogue of Quasars and Active Nuclei (Véron-Cetty and Véron 1987)—and four are galaxies. The only certain starburst galaxy (MS 0834.0+6517) has a flux of 1.7 × 10^{-13} ergs cm^{-2} s^{-1} and gives us a lower limit to the number of star-forming galaxies in the EMSS. To convert it to a lower limit in the integral counts we need to know the sky coverage of the EMSS at this flux. A simple interpolation of the values tabulated by Gioia and Maccacaro (1990) gives ~80 deg^2 (this is only approximate, since the quoted sky coverages are not appropriate for extended sources). We then obtain $N(>1.7 \times 10^{-13}) \gtrsim 1.2 \times 10^{-2}$ deg^{-2}, as shown in Figure 5. Although this estimate is based on one object, it seems to suggest that the surface density of starburst galaxies is larger than predicted using the S/I luminosity function (curves *a* in Fig. 5). We predict between six and 40 starburst galaxies brighter than the flux limit of the EMSS, depending on the choice of the luminosity function.

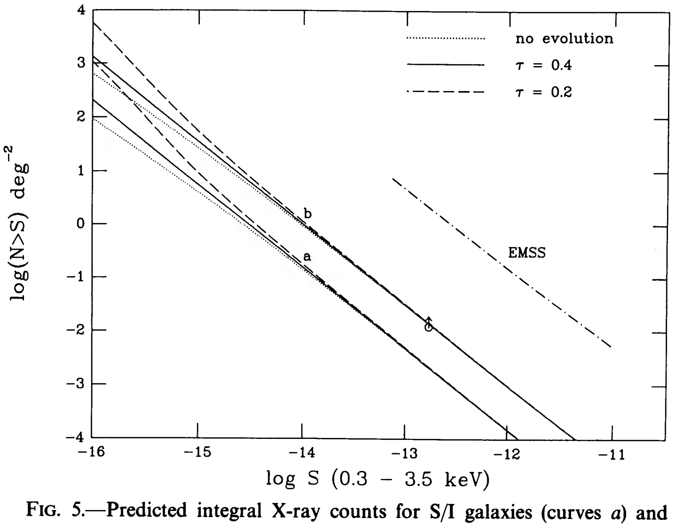

FIG. 5.—Predicted integral X-ray counts for S/I galaxies (curves *a*) and *IRAS* galaxies (curves *b*) for the cases of: no evolution (*dotted lines*); $\tau = 0.4$ (*solid lines*); $\tau = 0.2$ (*dashed lines*). The dotted-dashed line represents the integral counts for the extragalactic population of the Extended Medium Sensitivity Survey (EMSS). The open symbol indicates the only certainly identified starburst galaxy in the EMSS: it gives a lower limit to the surface density of starburst galaxies, since many more could be present in the survey (*see text*).

IV. METALLICITY AND THE XRB

It has been observed that the X-ray luminosity per O star in H II galaxies may be inversely correlated with metallicity (Fig. 6), an effect first noticed in the Magellanic Clouds (Clark *et al.* 1978), and also in the H II galaxy NGC 5408 (Stewart *et al.* 1982).

Whatever the reason for this dependence, which is presently not understood, it greatly increases the L_x of galaxies which are undergoing bursts of star formation in regions of low metallicity. It is difficult without further data on the correlation, and knowledge of metallicity with cosmic epoch, to estimate the true importance of metallicity on the integrated contribution of star-forming galaxies to the XRB. The above estimates (§ III) on the contribution of star-forming galaxies to the XRB have not included any effects of reduced metallicity at moderate to high redshift and are therefore conservative. If the average metallicity in star-forming regions at $z \sim 0.7$–1.0 is 10^{-2} to 10^{-3}, then the average X-ray luminosity would be higher by a factor of ~ 10 (Fig. 6), leading to an XRB almost certainly dominated by star-forming galaxies at moderate redshifts.

VI. SPECTRUM OF REDSHIFTED MXRB

It has been pointed out by several authors that subtraction of a composite AGN spectrum from the XRB leads to a very hard residual spectrum, which probably implies emission from compact, Comptonized sources (e.g., Giacconi and Zamorani 1987) or else from reflection-dominated sources (Fabian *et al.* 1990). Fabian (1988) has shown how the residual index depends on the subtracted component, with plausible residual spectra having indices ~ 0.2–0.3.

A composite spectrum for a star-forming galaxy may be constructed by averaging the spectra of MXRB in our own galaxy (e.g., Nagase 1989), together with some fractional contribution from medium and low-mass X-ray binaries. Although some MXRB have high-energy cut-offs at or above 20 keV, hard X-ray tails are by no means uncommon amongst these sources. The composite spectrum from Nagase is shown in Figure 7, which also indicates the effect of redshifting this composite spectrum, and compares it with the residual XRB. The composite binary spectrum can be redshifted to about unity and match the residual XRB very well. It may be concluded that the star-forming galaxy contribution to the ~ 2–10 keV XRB probably arises largely from redshifts in the range ~ 0.5–1.

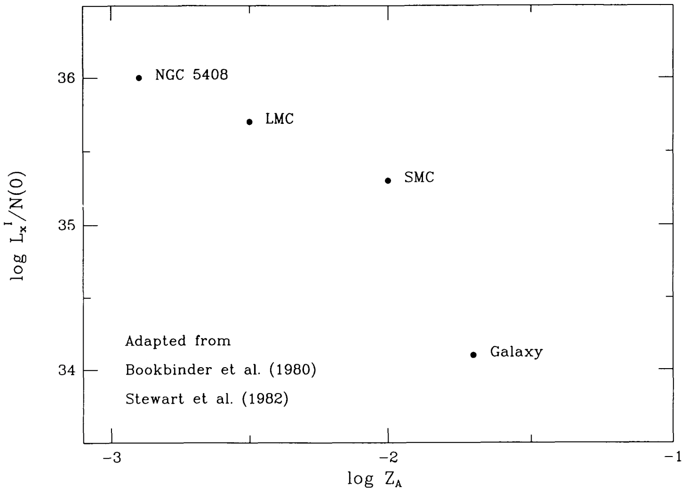

FIG. 6.—The effect of metallicity on the average X-ray luminosity of Population I sources per O-star in extragalactic H II regions. Data points are from Bookbinder *et al.* (1980) and Stewart *et al.* (1982).

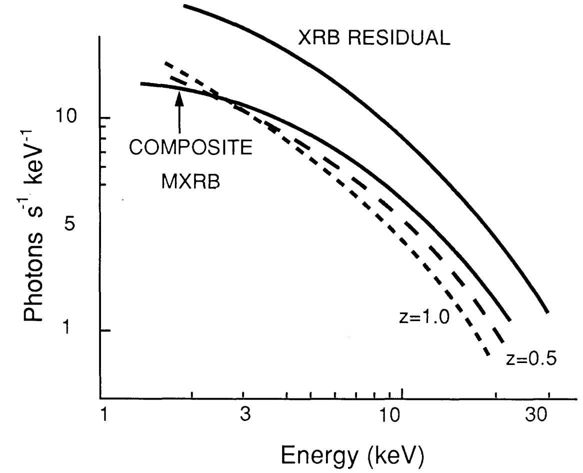

FIG. 7.—The composite spectrum of (mostly massive) X-ray binaries, and the effect of redshifts of 0.5 and 1.0. The shape of the residual XRB spectrum, after subtraction of the contributions of quasars and Seyferts, is shown for comparison. The ordinate scale has arbitrary normalization.

VI. CONCLUSIONS

We have presented plausible arguments that a major component of the XRB originates from star-forming galaxies. Plausibly, the X-ray emission from these objects is dominated by massive X-ray binaries, but our conclusions are based on observed luminosity functions and correlations, and are therefore largely independent of the emission mechanism.

We have found a strong correlation between X-ray and infrared luminosities ($L_x \propto L_{60\,\mu m}^{0.6-0.7}$) for both S/I and *IRAS* galaxies, using survival analysis techniques to take into account the presence of upper limits. Their X-ray luminosity functions, converted from the 60 μm ones using the X-ray/infrared relationship, have then been used to predict the X-ray number counts of star-forming galaxies and their contribution to the XRB at 2 keV. Our main results are the following:

1. The contribution of star-forming galaxies to the 2 keV XRB is in the 20%–30% range with moderate luminosity evolution ($\tau = 0.4$) and will dominate the XRB with an AGN-like evolution.

2. The effect of luminosity evolution on the X-ray counts will show up only at very low fluxes ($< 10^{-15}$–10^{-16} ergs cm^{-2} s^{-1}), beyond the range of current instruments and at the limit of *AXAF*; between six and 40 star-forming galaxies should be found in the EMSS. The first examples of these sources may already have been found in the Einstein Deep Surveys, especially in Pavo (Griffiths *et al.* 1990).

3. Based on spectral considerations, the dominant contribution to the XRB (2–10 keV) must arise from relatively low redshifts, i.e., at $z \leq 1$, but depending on the high-energy tail of the MXRB. This interpretation of the XRB therefore supports active star formation at relatively recent epochs.

A difficulty with the prediction of X-ray emission from MXRB in star-forming systems is that the metallicity is unknown and much of the activity may take place in dwarf galaxies or satellite galaxies, by direct analogy with our own Galaxy and the MXRB in the LMC/SMC; or in galaxies of low surface brightness. In this context, we note that York *et al.* (1986) and others have invoked a population of star-forming dwarf galaxies to explain QSO absorption line systems in intermediate and high-redshift galaxies.

VII. PREDICTIONS

We predict correlations between deep X-ray survey sources and: (1) Sub-MJy radio sources, as may have already been observed in the *Einstein* IPC deep survey data (Helfand *et al.* 1990); (2) Blue, emission-line galaxies (such as those found at moderate redshift by Broadhurst, Ellis, and Shanks 1988) especially in deep optical surveys such as those of Tyson (1988); (3) Deep far-infrared survey galaxies (such as those which will be detected with *ISO* and *SIRTF*).

In addition, we make the following predictions: (4) individual X-ray binaries commonly have iron-line emission at ∼6.4 keV, which should lead to a "bump" in the XRB spectrum at ∼3–4.5 keV; (5) deep surveys with *ROSAT* should detect larger numbers of star-forming galaxies than *Einstein*, especially from the hot winds emanating from the starburst galaxies (cf. M82), given the soft X-ray spectral range of *ROSAT*; (6) future large-area X-ray telescopes such as *XMM* need to have angular resoluton of $\leq 10''$ in order to avoid confusion between star-forming galaxies at very low flux levels; (7) discrete sources detected in the *AXAF* Deep Surveys will change in population as a function of X-ray energy, i.e., whereas AGN may dominate in the energy range ≤ 3 keV, active star-forming galaxies will become dominant in the energy range 3–8 keV. (8) A prediction of the star-forming galaxy origin of the XRB is, of course, that such galaxies have hard X-ray spectra, similar to those of MXRB in the Local Group. Verification of this will have to await *AXAF*, *XMM*, and other missions reaching X-ray energies of 8–10 keV.

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