Stellar contributors to the hard X-ray background?

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ABSTRACT

We use simple energetic arguments to estimate the contribution of massive X-ray binaries and supernova remnants to the cosmic X-ray background (XRB) at energies in excess of 2 keV. Recent surveys have shown that AGN probably account for most of the hard XRB ($E > 2$ keV), but there have been many suggestions that star-forming galaxies could emerge at fainter fluxes and perhaps account for a significant fraction of the soft and hard X-ray energy density. Assuming that the formation rate of massive X-ray binaries (MXRBs) traces the global star-formation rate, we find that their integrated contribution to the hard XRB can be estimated and is shown to be small (at less than the 1% level). Similarly, the integrated flux of SN is also shown to be insignificant, or at most comparable to MXRBs. AGN therefore remain the most viable candidates for producing the hard XRB, unless additional processes can be shown to dominate the global hard X-ray emission in distant starburst galaxies.

1 INTRODUCTION

Obscured AGN are now considered to be the most likely explanation for the bulk of the hard XRB. If this hypothesis is correct, the total energy output from these hidden AGN must exceed that of ‘ordinary’ (broad-line) objects by at least an order of magnitude (Fabian et al. 1998), with wide ranging implications. Existing deep X-ray surveys have already revealed what could be the ‘tip of the iceberg’ of this population. Several unambiguous cases of obscured QSOs have been detected (e.g. Almaini et al. 1995, Boyle et al. 1998, Fabian et al 2000) while at the faintest X-ray fluxes there is strong evidence for a large population of X-ray luminous emission-line galaxies (Boyle et al. 1995, Griffiths et al. 1996, McHardy et al. 1998). The true nature of this galaxy population remains controversial; however statistical cross-correlation studies clearly show that objects with a galaxy-like morphology contribute about $\sim 30\%$ of the soft ($< 1$ keV) XRB (Roche et al. 1995, Almaini et al. 1997). Results from the ultra-deep ROSAT survey of Hasinger et al. (1998) suggest that most of these ‘galaxies’ contain AGN (Schmidt et al. 1998), but the statistical sample is small. In addition, many of these faint sources were classified on the basis of high-ionisation optical coronal lines, which could (in principle) arise from supernova activity. In summary, there is no doubt that most of the $0.5 - 2$ keV XRB is produced by AGN, but there is the realistic possibility of a non-AGN contribution at the $10 - 20\%$ level.

Work has recently been undertaken at harder energies with ASCA and BeppoSAX resolving $\sim 30\%$ of the harder, $2 - 10$ keV background. Many of these sources have now been identified, and most appear to be absorbed AGN (Georgantopoulos et al. 1997, Fiore et al. 1999). Nevertheless, there is still the possibility of a starburst contribution at fainter X-ray fluxes (Moran et al. 1999). Only the deepest surveys with Chandra and XMM will resolve this issue. The latest results from the first such survey probe an order of magnitude deeper than before (Mushotzky et al. 2000) and claim to have resolved $\sim 75\%$ of the hard XRB. The nature of these Chandra sources is so far unclear, but the most likely explanation seems to be either absorbed AGN or possibly the first generation of quasars at very high redshift.

In this letter, we attempt to quantify the potential contribution of star-forming galaxies to the energy density of the XRB in a globally averaged sense. While this in itself is not a new suggestion (see Griffiths & Padovani 1990 and Treyer et al. 1992), recent determinations of the integrated star-forming history of the Universe (Madau et al. 1996; Lilly et al. 1996; Blain et al. 1999) enable a quantitative estimate of the X-ray emission from stellar processes at high redshift. Extrapolations based on no evolution models produce a negligible contribution, however, star-formation rates and SN rates were significantly higher during early epochs and so their integrated contribution over redshift can now be calculated. We use a recent determination of the star-formation rate of the Universe that combines optical and infra-red data (Blain et al. 1999) with observed properties of MXRBs and SN to estimate their probable contribution to the energy density of the XRB. Possible additional sources of hard X-ray emission are outlined in Section 4.

2 MASSIVE X-RAY BINARIES

MXRBs are produced in large numbers during bursts of star formation and are expected to dominate the X-ray emission from starburst galaxies (David, Jones & Forman 1992).
MXRBs are composed of a compact object (a neutron star or a black hole) accreting matter from a close O - B (Be) companion. Hard X-ray emission $E > 20$ keV results from the mass transfer process. About 50 candidate MXRBs have been detected in the Milky Way. They have thermal spectra with characteristic $T > 15$ keV and $L_X \sim 10^{37}$ erg s$^{-1}$ in the $E > 2$ keV band (van Paradijs & McClintock 1995). They are very short-lived, with life-times $t_{MXRB} \sim 10^5 - 10^6$ yr, much shorter than low mass X-ray binaries (LMXBs) which can last up to a Gyr. The contributions of MXRBs and LMXBs to the X-ray flux of our Galaxy are comparable. In the Milky Way, the majority of the MXRBs are X-ray pulsars, for which the accreting object is a magnetic neutron star. In low metallicity environments, such as the Magellanic clouds, the X-ray emission from MXRBs is enhanced, and hence the contribution from starbursts at high redshift (and low metallicity) could be much more significant than is observed locally (van Paradijs & McClintock 1995).

Several papers have addressed the issue of the contribution of star-forming galaxies (Bookbinder et al. 1980; Griffiths & Padovani 1990; Lahav et al. 1993; Treyer & Lahav 1996) and MXRBs to the hard XRB (Treyer et al. 1992). In all these treatments, the evolution of the X-ray luminosity function of galaxies is extrapolated to high redshifts in order to estimate the contribution to the XRB. Both groups concluded that newly forming galaxies could contribute up to 15% of the hard XRB, modulo the various uncertainties in the modeling of the evolution of the galaxy luminosity functions, and the conversion factor from the infra-red flux to X-ray flux. With the recent progress in observational determination of the globally averaged star-formation rate as a function of redshift (Madau et al. 1996; Lilly et al. 1996), the calculation of the total integrated emission in the hard band from MXRBs in vigorously star-forming galaxies is relatively straight-forward, if one assumes that the MXRB rate instantaneously tracks the star-formation rate.

2.1 Spectra and contribution to the hard XRB

We commence with the assumption that the MXRB rate as a function of redshift is proportional to the total star formation rate density $\rho_{MXRB}(z) \propto SFR(z)$. This amounts to assuming that for every solar mass of material that produces stars (given an IMF) with observed luminosity density, some fraction of that is processed into massive X-ray binaries. David, Jones & Forman (1992) find a tight relationship between the X-ray luminosity and the star formation rate in starburst galaxies from the IRAS Bright Galaxy sample, although there are recent claims that the scatter in the local group may be much larger. This proportionality is calibrated locally using fiducial values for the Milky Way: a star-formation rate of $1 M_\odot$ yr$^{-1}$ and a total integrated MXRB luminosity of $\sim 2.2 \times 10^{38}$ erg s$^{-1}$ in the hard X-ray band ($E > 2$ keV). This MXRB luminosity is based on the compilation of Dalton & Sarazin (1995), using the measured X-ray luminosities of the 8 known galactic MXRBs with peak X-ray luminosities in excess of $10^{36}$ ergs$^{-1}$. The fraction of the X-ray luminosity that is emitted in the hard band is estimated with a typical spectral energy distribution $f(E)$ for an MXRB that is well-fit by,

$$f(E) \propto E^a, \quad E < E_c$$

$$f(E) \propto E_c \exp\left(\frac{E_c - E}{a}\right) \text{ otherwise}$$

With this SED almost 90% of the X-ray emission is in the hard-band at $z = 0$. An effective k-correction needs to be applied to take into account the red-shifting of this SED out of the hard-band, which is done through the function,

$$f_{\text{hard}}(z) = \frac{\int_{0.1 \text{ keV}}^\infty f(E) dE}{\int_{0.1 \text{ keV}}^\infty f(E) dE}$$

Note that since the bulk of the star formation occurs at $z < 2$, including the effect of redshift MXRBs do indeed have the required spectral shape to explain the XRB at $E \geq 3$ keV. The integrated contribution from MXRBs to the hard XRB energy density is therefore;

$$\rho_{\text{MXRB}}(z) = \int_{z>0} f_{\text{hard}}(z) \xi_1 \left(\frac{\rho_{SFR}(z)}{1 M_\odot \text{ yr}^{-1}}\right) \times (1 + z)^{-7/2} \ dz \ \text{erg Mpc}^{-3},$$

where $\xi_1$ is the locally calibrated constant for $\Omega = 1$ and $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$. To illustrate the uncertainty in $\xi_1$, we write it explicitly in terms of the integrated MXRB luminosity function $\Sigma_i \mu L_X i$,

$$\xi_1 = 6.31 \times 10^{45} \left(\frac{\Sigma_i \mu L_X i}{2 \times 10^{38} \text{ ergs}^{-1}}\right).$$

One can then substitute the parametric form for $\rho_{SFR}(z)$ that is a good fit to both the optical and the far-infrared data from Blain et al. (1999), namely;

$$\rho_{\text{SFR}}(z) = \begin{cases} 0.009 \times 10^{0.6592z} M_\odot \text{yr}^{-1}\text{Mpc}^{-3} & z \leq 2.5 \\ 0.4 M_\odot \text{yr}^{-1}\text{Mpc}^{-3} & z > 2.5. \end{cases}$$

Note that star-formation in this model-fit continues at a constant rate out to high redshift. Another model that also fits current observations (the Gaussian model from Blain et al. 1999) produces very similar numbers. Integrating from $z = 5$ to $z = 0$, the contribution of MXRBs was found to be $2.26 \times 10^{34}$ erg Mpc$^{-3}$. The total energy density in the XRB is $2.63 \times 10^{57}$ erg Mpc$^{-3}$, 80% of which is in the hard band (Comastri 1998). MXRBs therefore contribute negligibly - of the order say 0.2%. Note that even if the IMF is biased toward high masses, increasing say, the total number of MXRBs by a factor of 10 or if the X-ray luminosities are higher in lower metallicity environments (van Paradijs & McClintock 1995), which is the case in high redshift starbursts or if X-ray luminosity is higher in very compact starbursts, then MXRB contribution to the hard XRB can be boosted to at most the few % level.

Our estimate differs from the results of previous work by Griffiths & Padovani (1990) and Treyer et al. (1992) due to reasons discussed below. Both those works had to assume detailed models for the relation between detected X-ray luminosity and either the optical luminosity or 60$\mu$m luminosity of star-forming galaxies and their evolution with redshift. Depending on their choice of assumed luminosity function, both studies concluded that star-forming galaxies could con-
3 THE CONTRIBUTION FROM SUPERNOVAE

In a typical galaxy, the total flux from the integrated number of SN over a Hubble time is roughly comparable to the luminosity of the central AGN, as we show below. The total energy output from SN can be estimated using the integrated SN rate from a given galaxy over a Hubble time with an assumed typical rate of 1/galaxy/100 yr = \(10^{-2}\)/galaxy/yr,

\[
E_{\text{SN}} \sim f_x \times \rho_{\text{SN}} \times t_H \times \epsilon_{\text{SN}}
\]

where the typical energy output from a SN \(\epsilon_{\text{SN}} = 10^{51}\) erg s\(^{-1}\), \(t_H = 10\) Gyr and \(f_x\) is the fraction of energy emitted in the X-rays by a typical SN. Note that this energy output is comparable to that from the central engine in AGN for \(f_x \sim 10^{-4}\),

\[
E_{\text{AGN}} \sim \epsilon f_{\text{AGN}} M_{\text{bh}} c^2
\]

Since AGNs are the primary discrete sources that contribute to the XRB, SN are expected to contribute as well. However, since the fraction of energy expelled in a supernova explosion that is emitted in X-rays is small, their contribution to the hard XRB is expected to be limited. Locally it is observed that hard X-rays can be produced by SN remnants via other processes, namely, by the presence of rare Crab-like objects, synchrotron radiation from shocks due to the collision of expanding shells and the inverse Compton scattering of infra-red photons off radio-emitting electrons (as possibly seen in M82). Detailed treatment of these mechanisms however, is beyond the scope of this work since we are averaging over the population as a whole, but we discuss additional sources of X-ray emission further in Section 4.

3.1 X-ray flux from SN

The star formation rate per unit volume quoted above is used to estimate the supernova rate per unit volume, wherein the variations from specific galaxy types are averaged over and the calibration is performed to the Milky Way (Madau, Della Valle & Panagia 1998). Of the typical energy output from a SN, \(E_{\text{SN}} = 10^{51}\) erg, only a very small fraction \((f_x)\) is emitted in hard X-rays. SN, in general, are rather inefficient in emitting X-rays, unless the local conditions under which they explode and expand include the presence of strong magnetic fields, or are in the dense interiors of pre-existing HII regions. The X-ray luminosities of detected bright SN and compact SN remnants are observed to be roughly \(L_X \sim 3 \times 10^{37}\) erg s\(^{-1}\) (Williams & Chu 1995), and with estimated mean ages of \(\sim 1000\) years,

\[
f_x \sim 10^{-3} \times \left( \frac{t_{\text{rem}}}{1000 \text{ yr}} \right) \times \left( \frac{L_X}{3 \times 10^{37} \text{ ergs}^{-1}} \right),
\]

where \(t_{\text{rem}}\) is the average age of the remnant. Note that here ‘age’ refers to the period that the remnant remains X-ray bright in the hard band, the overall life-time is expected to be much longer, of the order of \(10^9\) years or so. The integrated contribution from SN to the total energy density of the XRB is given by,

\[
\rho_{\text{SN}}(z) = \int_{z_{\text{max}}}^z \xi_z E_{\text{SN}} f_x n_{\text{SN}}(z) (1 + z)^{-7/2} dz \text{ erg Mpc}^{-3},
\]

where \(f_x\) is the efficiency of hard X-ray emission by the SN, \(E_{\text{SN}}\) is the typical energy output of a SN, \(E_{\text{SN}} \sim 10^{51}\) erg and \(n_{\text{SN}}(z)\) is the supernova rate in units of number per year per Mpc\(^{-3}\). Integrating the above equation using \(n_{\text{SN}}(z)\) computed from the star-formation rate in equation (5) for Type IIs and Type Ias, contributions of \(1.95 \times 10^{44}\) erg Mpc\(^{-3}\) [Type II] and \([5.89, 6.03, 3.66] \times 10^{53}\) erg Mpc\(^{-3}\) [Type Ias] (with time delays of [0.3, 1, 3] Gyr assumed between the SN explosion and the collapse of the primary star) were found. Clearly, Type IIs are more important than Type Ias, but their contribution to the hard XRB is only at the 0.1% level. Therefore, X-ray emission from ordinary SN cannot account for a sizeable fraction of the hard XRB; however, it is worth noting that SN are believed to contribute significantly to the gamma-ray background dominated by the \(\gamma\)-ray line emission from the decay of \(^{56}\)Ni, primarily from Type Ia's (see Watanabe et al. 1998).

3.2 Supernovae in compact, dense environments

SN exploding in high-density environments can rapidly reach very high X-ray luminosities, perhaps high enough to power the broad-line region of some AGN (e.g, Terlevich et al. 1992). A good example is SN 1988Z, detected by Fabian & Terlevich (1996), the most distant SN yet detected in X-rays. These SN achieve maximum luminosity and very high temperatures \((\sim 30\text{ keV})\) soon after the explosion \((t \sim 1\) yr). Thereafter they cool and the luminosity decays roughly as \(L_x \propto t^{-11/7}\) (see Fabian & Terlevich 1992 and references therein) with luminous lifetimes of \(10 - 100\) years.

These events are much more efficient generators of X-ray emission. Taking SN 1988Z as a prototypical example, one finds that \(\sim 2\) per cent of the total energy of the supernovae can be eventually liberated in X-rays, an order of magnitude higher than “ordinary” supernovae. Such events will clearly boost the potential supernovae contribution to the hard XRB. To place an upper bound on this contribution, one can assume that \(all\) supernovae occur in such environments and scale to the supernova rate as above. This leads to an upper limit of \(1 - 2\%\) to the total XRB energy density.

4 ADDITIONAL SOURCES OF HARD X-RAY EMISSION?

In this work we concentrate on the ‘classic’ sources of X-ray emission from starburst galaxies, namely X-ray binaries and emission from supernovae. However there are additional sources of X-ray emission which, potentially, could significantly boost the starburst contribution to the hard X-ray background. Taking these in turn:
4.1 Compton scattering of IR photons

There is plausible evidence in at least two local galaxies (M82 and NGC3256) that IR photons can be Comptonised to X-ray energies by the relativistic electrons produced by supernovae (Moran & Lehnert 1997, Moran, Lehnert & Helfand 1999). Given the vast reservoir of IR photons produced by starburst activity, even a relatively low Comptonising efficiency can produce significant X-ray emission. Estimating the expected X-ray luminosity is highly uncertain however, and requires detailed knowledge of the geometry and energy budget in the Synchrotron plasma. Nevertheless, such models are strong candidates for explaining the hard X-ray emission in M82 and NGC3256. The possibility that these processes are globally important for starburst galaxies cannot be ruled out.

4.2 Crab-like Synchrotron sources

Crab-like SNRs ("plerions"; Weiler & Panagia 1978) are rare Synchrotron dominated X-ray sources. Synchrotron emission is unusual in X-ray astronomy due to the exceptionally high magnetic fields required and the short radiative lifetimes, but the handful of Crab-like objects known are important, highly luminous exceptions. One cannot exclude the possibility that extreme, Crab-like objects may be more important in early star forming galaxies, although so far there is no evidence to support this.

4.3 Starburst driven super-winds

Many local starburst galaxies show evidence for energetic outflowing winds (e.g. Heckman et al 1996). These winds can account for roughly 50 per cent of the X-ray luminosity in the soft (ROSAT) X-ray band but with typical thermal temperatures of < 1 keV they are not expected to contribute significantly at higher energies.

5 CONCLUSIONS AND DISCUSSION

In this letter, the contribution of MXRBs and SN to the hard XRB have been computed using recent estimates of the globally averaged star-formation rate in the Universe. It is found that MXRBs contribute at the 1% level and that the contribution of SN is probably significantly lower. Taking into account the uncertainties in the efficiency of hard X-ray emission and its unknown dependence on metallicity, MXRBs can at most account for a few percent of the hard XRB, despite their optimal spectral shape. Likewise, if most early supernovae occur in highly compact environments, their potential contribution could rise significantly, but still produce only ~ 1 – 2% of the hard XRB. We conclude that AGN will dominate the source counts in forthcoming X-ray surveys with Chandra and XMM unless the X-ray emission from distant starburst galaxies is dominated by alternative processes. Compton-scattering of IR photons by relativistic electrons and/or a hitherto unrecognized abundance of Crab-like synchrotron sources would boost the hard X-ray emission from starburst galaxies significantly, but as yet the universal role of such phenomena is unclear.

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REFERENCES

Miyaji, T., Hasinger, G., Schmidt, M., 1999, proceedings of the Oct. conf. in Maryland, ‘When galaxies were young’
Snowden, S. L., 1998, Lecture Notes in Physics, 506, 103

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   Lewin, van Paradijs & van den Heuvel, Camb. Univ. Press,
   Cambridge, 58
   Nachr. 319, 67