THE X-RAY BACKGROUND: ORIGIN AND IMPLICATIONS

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This paper will be concerned with three topics relevant to the X-ray background: (i) X-ray emission mechanisms in quasars; (ii) the contributions to the X-ray background from quasars, clusters of galaxies, intercluster gas, young galaxies, etc; and (iii) the use of X-ray background observations as a probe for large-scale density irregularities in the Universe.

1. X-RAY EMISSION FROM QUASARS

In the new era of X-ray astronomy initiated by HEAO 2 (the "Einstein Observatory"), remote quasars and active galactic nuclei can be studied in detail in the X-ray band as well as at optical (and sometimes radio) wavelengths. These exciting developments are reviewed by Giacconi elsewhere in this volume. My main topic is the X-ray background - its implications as a probe for the evolution and large-scale structure of the Universe. Quasars and related objects apparently make a major contribution to this background; it may therefore be appropriate briefly to consider the mechanisms whereby X-rays can emanate from such objects. At the moment, such inferences as we can draw concerning physical conditions in the emitting volumes suggest that a wide variety of processes could generate X-rays.

Optical data on the broad emission lines imply that these arise from clouds moving at speeds of several thousand km s^{-1}. Shocks involving this kind of velocity automatically yield gas at temperatures of $\gtrsim$ 10 keV: indeed, the clouds giving the optical emission lines ($T_e \simeq 10^4$ °K) may be in pressure balance with a hot and more rarified medium capable of emitting thermal X-rays via bremsstrahlung, or comptonisation of soft photons. We also observe directly that quasars emit non-thermal continuum radiation, implying that relativistic electrons are present. (These particles could have been accelerated via shocks, or by some electromagnetic process near a massive central object.) These can give X-rays via synchrotron or compton emission. The various possible processes can be summarised in a flow diagram reproduced in Figure 1.

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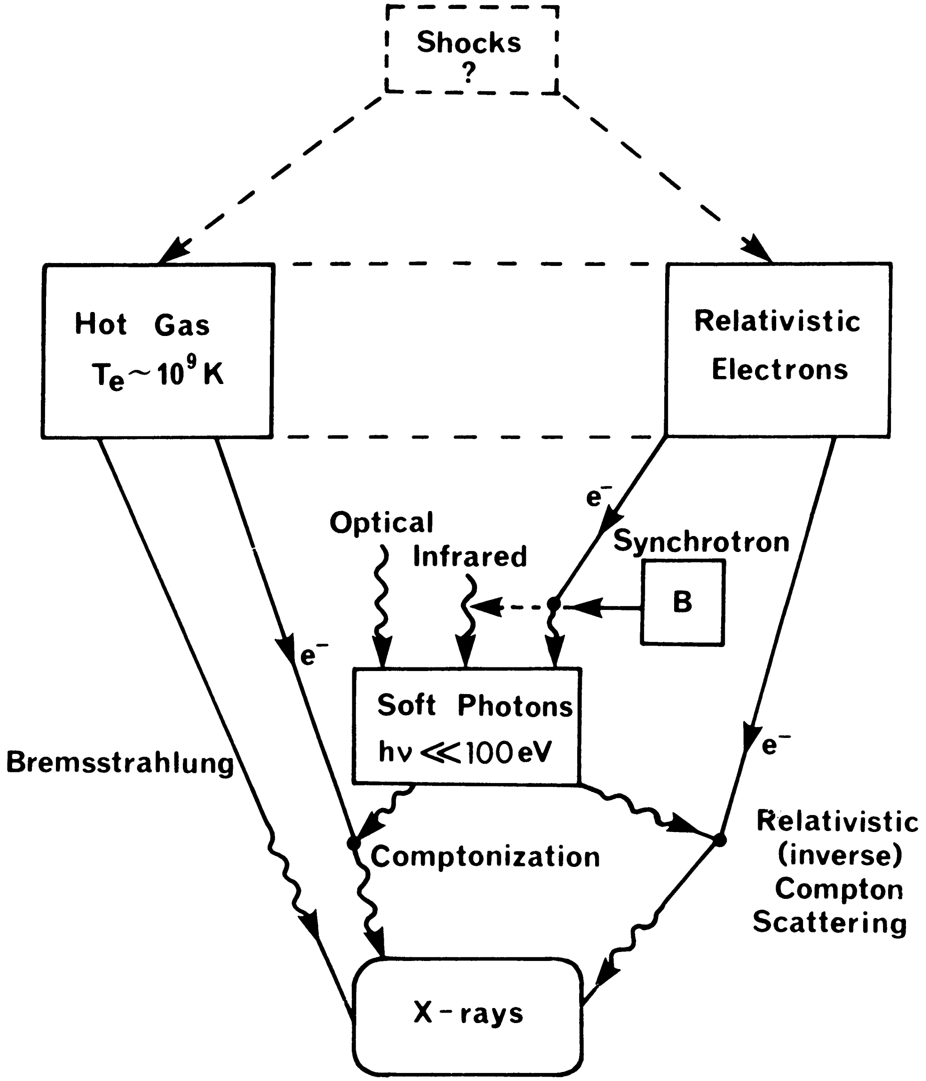

Figure 1. Possible pathways for X-ray emission in galactic nuclei (from Fabian and Rees (1978a), in which a fuller discussion of these various mechanisms can be found).

The gas responsible for the broad emission lines - even for Lyman α - has densities $n_e \lesssim 10^{11}$ cm^{-3}; photoionization models then suggest that this gas lies $\gtrsim 10^{18}$ cm from the central continuum, and that it consists of enormous numbers of fast-moving clouds of individual dimensions $\lesssim 10^{15}$ cm (Blumenthal and Mathews 1979; Carswell and Ferland 1979). There is no physical reason why, still closer to the central non-thermal continuum, there should not be even denser ($n_e \gg 10^{11}$ cm^{-3}) and more opaque clouds. Indeed, in a wide class of accretion models (Bergeron 1979; Maraschi et al. 1979), infalling clouds could exist, with $(n_e T_e) \propto r^{-5/2}$, in pressure balance with a "hot-phase" medium at the virial temperature. At a distance r from the centre, the equivalent black body temperature is

$$T_{bb} \simeq 5 \times 10^4 L_{47}^{\frac{1}{4}} (r/10^{15}\ \mathrm{cm})^{-\frac{1}{2}}\ \mathrm{K}$$

(the non-thermal continuum luminosity, $10^{47} L_{47}$ erg s^{-1}, being assumed to come from a central region of size $r_{cont} < r$). In the high density limit, clouds located where $T_{bb} \gtrsim 10^4$ K would have $T_e \simeq T_{bb}$ and would reprocess the incident continuum into approximately black body radiation. The form of the reprocessed continuum depends on the configuration and dynamics of the clouds - specifically, on how the covering factor depends on radius for $r_{cont} \lesssim r < r_2$, where r_2 is the radius such that $T_{bb}(r_2) \simeq 10^4$ K. Recent IUE data on 3C 273 (Ulrich et al. 1979) reveal evidence for such a "thermal" continuum feature. The dense clouds at $r \ll 10^{18}$ cm may be embedded in a hot (almost relativistic plasma) which radiates non-thermally or by comptonisation of the soft photons generated by the cool clouds (cf. Liang 1979).

To discriminate among the various mechanisms illustrated in Fig. 1, further extended spectral observations covering the hard X- and γ-ray bands are needed. These, combined with variability timescales, may eliminate some emission mechanisms. Highly variable sources seem most likely to emit via non-relativistic Compton scattering, the timescales for this process being shorter than for bremsstrahlung from the same electrons. Relativistic Compton scattering seems unable to produce short timescales without multiple scattering being important, thereby creating an energy problem and predicting dominant γ-rays. The bulk of the material in the emitting region may be mildly relativistic ($T_e = 10^9 - 10^{10}$ °K). Observations of X-rays from galactic nuclei should stimulate much needed study of processes such as: radiation processes in 'transrelativistic' plasmas where electron-electron bremsstrahlung and relativistic corrections are important; production of $e^+ - e^-$ pairs, and their effects on cooling and opacity; effects of major differences between electron and ion temperatures; comptonisation of spectra in inhomogeneous gas clouds; and acceleration of ultrarelativistic particles by mildly relativistic shocks.

X-ray observations - along with studies of the non-thermal optical continuum - offer the most direct evidence on physical conditions close to the central "power house" (dimensions $\lesssim 10^{15}$ cm). Relative to the continuum source, even the broad-line region is diffuse "fuzz" out on the periphery, $10^2 - 10^3$ times further removed from the centre.

2. ORIGIN OF X-RAY BACKGROUND

2.1 The Contribution from Quasars

Preliminary data from the first deep surveys carried out with the Einstein Observatory, covering only of order one square degree, and reported by Giacconi elsewhere in these proceedings, show that most quasars down to ∿ 19th magnitude are detectable as X-ray sources. The limiting sensitivity is $\sim 10^{-14}$ erg $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in the 1 - 3 keV band, $\sim 10^{3}$ lower than earlier surveys. This is not a surprising result - it was predictable from the scanty previous data if the ratio of X-ray and optical luminosities for the typical quasars was similar to that of 3C273 and Seyfert nuclei. Setti and Woltjer (1973, 1979) and others have pointed out that only a modest extrapolation from the Einstein Observatory limiting sensitivity would account for all the X-ray background (at $\lesssim$ 5 keV): indeed, the argument can now be inverted, and the X-ray background used to set constraints on how far, and how steeply, the quasar counts can be extrapolated to fainter magnitudes (Fabian and Rees 1978b, Setti and Woltjer 1979). See Figure 2 and caption for further explanation. This sets constraints on the evolution with z of the quasar population, and on extrapolations of the luminosity function towards fainter objects (Seyfert galaxies, etc.).

The parameter α_{OX} - denoting the spectral index that is obtained by interpolating a power-law spectrum between the optical (2500 Å) and X-ray (2 keV) flux densities - shows no obvious correlation with luminosity or redshift (Tananbaum et al. 1979; Avni et al. 1979). This gives us some confidence in assuming that the X-ray counts do indeed have the same slope as the optical counts. However it will be important, both for cosmological applications and for our physical understanding of quasars and their evolution, to test this by studying the counts and redshift distribution for an X-ray selected sample. (There should soon be a large enough sample to permit an analysis similar to Schmidt's (1970) well-known comparison of an optically-selected and a radio-selected sample.)

The Einstein Observatory data refers to relatively low energy X-rays (below ∿ 4 keV). One needs some spectral information before one can estimate how much quasars contribute to the $\gtrsim$ 10 keV X-ray background.

At the time of writing, the best evidence on the X-ray spectra of active galactic nuclei comes from the work of Mushotsky et al. (1979) using the HEAO-A2 experiment, which covers the energy range 2 - 50 keV (Holt 1979). Of the seven Seyfert nuclei in the sample, all are roughly fitted, above 5 keV by power laws with (energy) spectral index $\alpha \simeq 0.6$. NGC4151 has a flatter spectrum, which may continue all the way up to γ-ray energies, but there is otherwise no correlation between α and L_X, even though the sample contains a range of ∿ 100 in L_X. Below 5 keV there are two other features: a (possibly variable) cut-off due to absorption; and a low energy "excess", with $\alpha \simeq 2$, which may also be variable. The 5 "BL Lacs" in the sample show two components: one "hard", with $\alpha \simeq 0.2$; the other "soft", with $\alpha \simeq 2$.

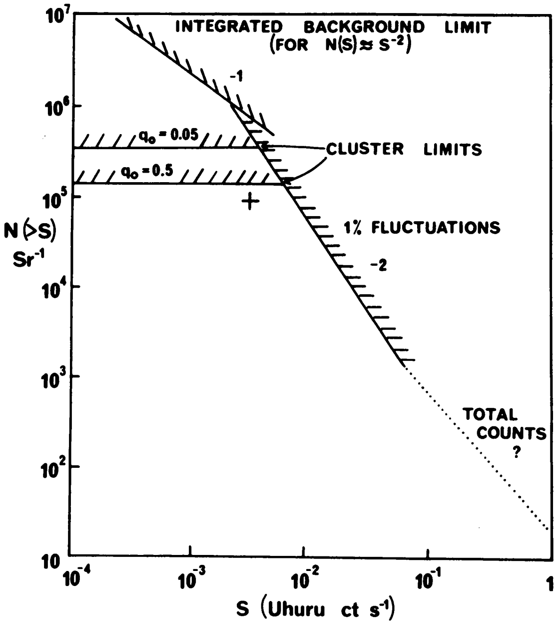

Figure 2. Integrated background and fluctuation constraints plotted in Uhuru flux units ($\simeq 1.1 \times 10^{-11}$ erg $cm^{-2} s^{-1}$ at 1 - 3 keV). These constraints depend in detail on the actual source counts, and thus are only approximate; the lines drawn (logarithmic slopes -1 and -2 respectively) do however indicate the limits set by the integrated background (assuming $N(> S) \propto S^{-2}$), and the absence of detected fluctuations in the background, respectively (Fabian and Rees 1978b). The total surface density for rich clusters out to $z \simeq 3$, assuming a number density 4×10^5 $(c/H_0)^{-3}$, is indicated for $q_0 = 0.5$ and $q_0 = 0.05$: it is clear that rich clusters, however they may evolve, cannot reach the integrated background line without contradicting the fluctuation constraints. The cross denotes a point on the source counts estimated by Giacconi et al. (1979) from the Einstein Observatory's first deep surveys. Most of these sources may be quasars. This point lies on an extrapolation, with logarithmic slope -1.5, of the counts at high flux densities. This is, however, fortuitous: most of the Uhuru-level extragalactic sources are clusters, whose counts probably have a slope flatter than -1.5; the quasar counts may be as steep as -2, in which case only a modest further extrapolation to fainter fluxes suffices to account for the entire X-ray background.

Evidence on the hard X-ray spectra of bona fide quasars is even more sparse, being restricted essentially to 3C 273 (Worrall et al. 1979). This object shows ∿ 40% variations on timescales of 6 months, with α in the range 0.4 - 0.7 between 5 and 50 keV. The spectrum seems steeper both at lower and at higher energies (there is a measurement by CosB of ∿ 100 Mev γ-rays from 3C 273 (Swanenberg et al. 1978)).

According to Avni et al. (1979) α_{OX} varies between 0.94 and 1.86. The mean is 1.27 (though this refers to a sample biased in favour of radio-selected quasars). The fact that the X-ray spectral index is flatter than α_{OX} has the astrophysically-interesting consequence that the luminosity of quasars is concentrated in the optical/UV band or in the hard X-ray band. As far as the X-ray background is concerned, the X-ray spectral index of quasars seems flat enough to ensure that - given that they are a major contributor at $\lesssim$ 5 keV - they may also contribute most of the background at higher energies: indeed the fact that the γ-ray background is not stronger allows us already to exclude the possibility that most active nuclei have spectra like NGC 4151.

2.2 Clusters of Galaxies

The X-ray properties of clusters are reviewed by N. Bahcall elsewhere. In clusters such as Coma there now seems little doubt that most of the X-rays below ∿ 10 keV are thermal bremsstrahlung from metal-enriched gas in the core of the cluster. We know much less about the gas in the outlying parts of clusters because its emissivity ($\propto n_e^2$) is low - it may not be in equilibrium and its temperature and composition are uncertain. The properties of small groups and "unrelaxed" clusters such as Virgo are more complex. The X-ray luminosity of rich clusters seems positively correlated with virial velocity, cluster richness and central density; but negatively correlated with the fraction of spirals in the cluster. The latter is in accord with ideas that, in "dynamically old" clusters, the gas has been stripped from individual galaxies.

Some consideration of how clusters evolve is a prerequisite not only for understanding their present properties, but also for interpreting the data on large-redshift clusters that HEAO-B is now providing, and for pinning down the cluster contribution to the X-ray background.

Two contrasting hypotheses have been explored:

A. Galaxies (and dark matter) may have condensed from primordial gas before clusters assemble. Galaxies then gradually aggregate into clusters in a manner that can be simulated by gravitational N-body computations. The present gas in clusters then results from either: infall of the small fraction of material (∿ 10%) that escaped incorporation into the first generation of gravitationally-bound systems; or ejection from galaxies, via stellar winds and planetaries, supernovae, "sweeping" of interstellar matter by ram pressure of pre-existing cluster gas.

B. Protoclusters (i.e. gas clouds of $\sim 10^{14}$ $M_{\odot}$) may have been the first objects to have condensed out of the expanding universe; they then cool and fragment into galaxies. In this scheme, advocated particularly by the Moscow group (Doroshkevich et al. 1974), the present intracluster gas represents material that has not (yet) cooled and condensed.

Obviously a type-A hypothesis yields clusters whose X-ray luminosities increase with time; on the other hand, hypothesis B would predict that clusters were brightest where they had just virialised but were still predominantly gaseous, but that the X-ray luminosity would thereafter decline as the initial gas gradually cooled and condensed into galaxies.

Perrenod (1978) and others have investigated type-A models. The general findings are that L_X may increase by a factor up to $\sim$ 10 between the epoch corresponding to $z \simeq 1$ and the present. This is a combined consequence of the cumulative build-up of gas, and the deepening of the cluster potential well as virialisation proceeds.

The X-ray emission from clusters may turn on more suddenly than in Perrenod's schemes: for instance, gas could perhaps be retained in galactic halos (at temperatures $kT \lesssim 1$ keV) until the galaxies fall together into a cluster and the halo material is stripped away and shock-heated to the cluster virial temperature (Norman and Silk 1979). One difficulty stems from the fact that the hypothesised halo gas has a short cooling time; on the other hand, the Butcher-Oemler (1978) evidence for a sharp evolutionary change in galaxy colours (indicating a sudden quenching of star formation) supports this general idea, at least qualitatively.

Observations of distant clusters with the Einstein Observatory offer our best hope of discriminating between these various schemes. In practice, a broad range between the extremes of A and B seem possible within the limits of current observation. Preliminary data on a small sample of clusters with $z \simeq 0.5$ can merely rule out extreme evolution of either sign (Henry et al. 1979).

Rich clusters probably contribute 5 - 10% of the $\lesssim 5$ keV X-ray background - one can rule out the possibility that they contribute all the background - in whatever fashion they may evolve - because the small angular scale fluctuation limits imply that the total number of contributing sources must exceed the number of rich clusters out to $z \simeq 3$ (Fabian and Rees 1978b).

2.3 Ultra-hot Intercluster Gas?

The gas temperatures in clusters are $\sim$ 5 keV, implying an exponential fall-off in their contribution to the background at higher energies. One possible contributor to a genuinely diffuse hard X-ray background might be thermal bremsstrahlung from a very hot gas between the clusters. As has recently been emphasised by the Goddard group (Marshall et al. 1979) the background spectrum is, empirically, very closely fitted by a 35-40 keV bremsstrahlung spectrum. The excellence of this fit may well be fortuitous: indeed the fit could be destroyed by merely subtracting off the contributions from other sources of background (e.g. quasars and clusters), which are known to be substantial below 10 keV and do not have this spectrum.

Field and Perrenod (1977) discussed the possibility that intergalactic gas is indeed responsible for the background. If such gas is reheated at redshift z_{heat} to a temperature such that $kT = 35(1+z_{heat})$keV, then it can emit the entire X-ray background if its density corresponds to

$$\Omega_{gas} \simeq \frac{1}{3}\left((1+z_{heat})^{1.6} - 1\right)^{-\frac{1}{2}} h_{100}^{-3/2} \qquad (1)$$

Of course, less gas would be needed if it were clumped; but at such high temperatures it would be uninfluenced by the gravitational field fluctuations arising from clusters of galaxies.

The main difficulty with this hypothesis, as Field and Perrenod realised, is the energy requirements for heating such a large mass of gas. Subsidiary problems relate to the Compton distortions of the microwave background spectrum that this ultra-hot gas would cause (Wright 1979); also, conductivity and pressure balance considerations might prejudice the existence and survival of low-density HI clouds around galaxies.

2.3 Other Possible Classes of Extragalactic X-ray Sources

Compton scattering in remote radio sources. Inverse Compton scattering of microwave background photons by relativistic electrons was long ago suggested as a contributor to the X-ray background (Felten and Morrison 1966). This process would tend to be more efficient at large redshifts, for two reasons: the energy density of the microwave background varies as $(1 + z)^4$; and the many suppliers of relativistic electrons - radio source, quasars, etc. - were more prolific at early epochs. As a corollary of this effect, Compton scattering may "snuff out" extended sources at large redshifts (Rees and Setti 1968).

X-rays observed in the range 1 - 10 keV are generated predominantly by electrons with Lorentz factors in the range $(1 - 3) \times 10^3$. The radio sources with the highest inverse Compton X-ray luminosities are therefore those with the largest energy content in the form of such electrons. These sources will not necessarily be those with the highest radio luminosities: the maximum stored energy is inferred to exist in very extended "giant" sources and in the low surface-brightness "bridges" joining the components of some strong double sources. On the assumption of equipartition, the energy stored in $\gamma \simeq 10^3$ relativistic electrons in NGC 6251 and 3C 236 is $\gtrsim 10^{60}$ erg (Waggett et al. 1977; Willis et al. 1974).

If the magnetic field is weaker than its equipartition strength, the inferred energy stored in relativistic electrons is even larger. Some of the X-rays seen from Centaurus A are probably inverse Compton emission from the inner radio lobes (Schreier et al. 1979).

A radio source with a typical spectra index ~ 0.7 containing $10^{60}\ \varepsilon_{60}$ erg of relativistic electrons with $\gamma \gtrsim 10^3$, and at redshift z, will emit an inverse Compton X-ray power of $\sim 3 \times 10^{43}\ (1+z)^4\ \varepsilon_{60}$ erg/s. We do not know the appropriate values of ε_{60}, but it would seem quite probable that there may be diffuse objects at $z \simeq 2$, a few hundred kpc in extent, emitting $\sim 10^{46}$ erg of 1 - 10 keV X-rays. These sources would generally not be particularly powerful radio sources (objects such as Cygnus A or 3C 9 are powerful radio sources because they have a strong magnetic field, rather than because they have an exceptional energy content), but they may feature in deep radio surveys. Several Westerbork radio sources have already been identified in Einstein Observatory deep surveys, though it is not yet clear whether the X-rays come from the radio lobes or from the active nucleus (Giacconi et al. 1979).

Young galaxies. According to some theories, galaxies pass through a bright early phase when the rate of star formation, supernova outbursts, etc. is ~ 100 times higher than in a present-day galaxy (e.g. Meier 1976, Ostriker and Thuan 1975). The properties of such systems, and their potential detectability, depend on many uncertainties; but we can readily see that a young galaxy where supernova outbursts were frequent could give rise to thermal or non-thermal X-rays with a much higher power than a present-day galaxy.

Winds from young galaxies. A possible mechanism that could generate a 40 keV bremsstrahlung-type spectrum without demanding such a high mass of gas might be supernova-driven winds in young galaxies. Mathews and Baker (1971), Mathews and Bregman (1978) and others have discussed galactic winds. The mass is supplied by supernova ejecta, with characteristic velocities of $\sim 10^4$ km/sec (~ 100 keV per particle), and by more gentle processes such as stellar winds and planetary nebulae. Supernovae give the main energy input, though not necessarily the main mass supply. Two simple requirements for a wind are

$$\dot{M}_{SN}/(\dot{M}_{SN} + \dot{M}_{other}) \gtrsim \frac{\text{(escape energy, per proton, from galaxy)}}{100\ \text{keV}} \qquad (2)$$

and

$$t_{cool} \gtrsim t_{outflow} \qquad (3)$$

(Note that these constraints could perhaps be eased in a more complex - though maybe more realistic - case when the gas has a multiphase structure.)

For a given value of the ratio (2), condition (3) is more easily satisfied now than in the past. However, galaxies might have experienced an initial bright phase when supernovae provided the main mass loss. There would then have been a very fast ($\sim 10^4$ km/sec) hot ($\sim$ 100 keV) wind emanating from young galaxies. For instance the supernova rate within the core region of a young galaxy may be high enough to sustain, for $\sim 10^7$ yrs, a wind with kinetic energy output $\sim 3 \times 10^{46}$ erg/sec. Even though (3) is fulfilled by an unduly wide margin, such a wind would yield $\sim 5 \times 10^{44}$ erg/sec, per galaxy, in hard X-rays (Bookbinder et al. 1979). If their upper-main-sequence stars have a Population I composition, young galaxies may be stronger X-ray sources than present-day galaxies because metal-poor stars spend longer in the part of the H-R diagram that permits strong radiation-driven winds, so the lifetime of a typical X-ray binary is correspondingly prolonged.

2.4 The Background Spectrum

The well-known problem of accounting for any sharp break or feature in the background spectrum will be reassessed by di Zotti in his contribution. If various categories of source contributing to the background have different spectra, there is of course no reason why the degree of isotropy should be similar at different X-ray energies (cf. Rees 1973).

3. THE BACKGROUND AS A PROBE OF LARGE-SCALE INHOMOGENEITY

The X-ray background obviously holds important clues to the evolutionary history and spatial distribution of its sources. I shall mention here just one aspect of this subject: the sensitivity of the X-ray background as a probe for density irregularities on scales larger than superclusters. Whatever the precise origin of the background may be, it is plausible to suppose that any large scale inhomogeneities in the overall distribution of gravitating matter will give rise to associated inhomogeneities in the spatial density of X-ray sources. (This relation may not be a strict proportionality - the X-ray source density or emissivity may depend on a higher power of the overall density - but this would do no more than change a numerical coefficient of order unity in the following expressions, where we consider only small fractional perturbations.)

Although the covariance function data become imprecise on scales exceeding 20 Mpc, the universe definitely appears more homogeneous on scales $\gtrsim$ 100 Mpc than on any scale $\lesssim$ 10 Mpc. There is good radio, and optical evidence that the distribution on the sky of all kinds of luminous objects becomes smoother as we look deeper.

Fluctuations on larger scales ($\lambda \gtrsim$ 100 Mpc, say) are thus only of small amplitude (certainly $\delta\rho/\rho \lesssim 1$). Their influence may nonetheless be significant. This is because the velocity perturbations that they induce are of order

$$V_{pec} \simeq c\Omega \left(\delta\rho/\rho\right) \left(\lambda/\lambda_H\right) \qquad (4)$$

and the gravitational field perturbations are

$$\Delta\phi \simeq c^2\Omega \left(\delta\rho/\rho\right) \left(\lambda/\lambda_H\right)^2 \qquad (5)$$

This means that peculiar velocities are dominated by the largest scales unless $\delta\rho/\rho$ falls off more steeply than λ^{-1} ($\propto M^{-1/3}$). Anisotropies in the microwave background on small angular scales are due to gravitational and doppler effects on the 'cosmic photosphere' (the gravitational effect dominating for scales exceeding the horizon size at that epoch (Sunyaev and Zeldovich 1970)).

Constraints are placed on large-scale inhomogeneities by the isotropy of any class of extragalactic discrete source; but these are of limited value. Inferences drawn from optical counts of galaxies are bedevilled by the possible effects of patchy Galactic obscuration; for radio sources, absorption is negligible but the problem here is the broad luminosity distribution (such that intrinsically faint nearby sources and powerful remote ones appear in surveys in comparable numbers at the same flux density). As discussed by Fanti in these proceedings, the best limits amount to $\lesssim 5$ % on scales of $\sim$ 1/3 the Hubble radius.

Given that the X-ray background is predominantly from cosmological distances ($z \gtrsim 1$), and that the Galactic contribution, away from the plane, is only a small contamination, X-ray data can provide useful evidence on the distribution of matter, if we assume that the X-ray emission per unit volume (at a given epoch) scales with the overall matter density. The present isotropy limits have a precision of about 1 per unit on large angular scales. Warwick et al. (1979), in an analysi of Ariel V data, (2 - 18 keV) obtained an upper limit of better than 1 per cent to any 24h effect, after subtracting off a component depending on galactic latitude. The limits on angular scales of $\lesssim 20^\circ$ are no better than a few percent, but there are prospects of significant improvements from larger-area detectors, and from measurements at higher energie where the Galactic disc contributes relatively less.

Suppose that the input into the X-ray background at a redshift z amounts to a power per unit comoving volume of $\mathcal{E}(z)$. The background intensity then involves an integral of the form

$$\mathcal{I} = \frac{c}{4\pi} \int \mathcal{E}(z)\,(1 + z)^{-\alpha}\,\frac{dt}{dz}\,dz \qquad (6)$$

where α is the effective spectral index, and dt/dz depends on the cosmological model. It is convenient to define a number

$$x = \frac{c}{4\pi} \mathcal{E}(0)\ H_o^{-1} / \mathcal{J} \qquad (7)$$

The significance of this number is that a static non-evolving Euclidean universe of radius cH_o^{-1} would emit x times the actual X-ray background. The value of x is of order unity: the $(1+z)^{-\alpha}$term in (6) tends to reduce it below unity; on the other hand, any evolutionary effect which enhanced the contribution from large z would tend to raise it.

Clumping of the sources, on any scale, would cause a corresponding anisotropy or 'graininess' in the observed X-ray background. Suppose, for illustration, that the clumping has a characteristic (comoving) scale λ (<< the present Hubble radius) and that the amplitude of the variations is $\delta\rho/\rho$. In general $(\delta\rho/\rho)$ will be a function of z. The inhomogeneities nearest to us will cause anisotropies in the X-ray background. The precise amplitude depends on the configuration of the irregularities around us, but the characteristic expected amplitude is obviously

$$\left(\frac{\Delta I}{I}\right)_x \simeq x\left(\frac{\delta\rho}{\rho}\right)\left(\frac{\lambda}{\lambda_H}\right) \qquad (8)$$

Additionally, there will be fluctuations on small angular scales $\sim(\lambda/\lambda_H)$ due to similar irregularities at redshifts $z \gtrsim 1$. (Turner and Geller (1979) have already been able to show that the X-ray background is uncorrelated with observed bright galaxies, to a precision which implies sufficient source evolution to make x twice as large as its non-evolutionary value.)

If the irregularities in the X-ray emissivity are related to inhomogeneities in the distribution of matter, then the gravitational effects should induce peculiar velocities, which themselves show up as '24h effects' in the X-ray and microwave background. This relationship is complicated in the general case where the perturbations have become non-linear. Things are simpler, however, if we restrict attention to perturbations whose gravitational influence makes merely a small fractional change in the Hubble flow, as seems to be the case for all scales $\gtrsim$ 20 Mpc (the scale of the Local Supercluster). These linear perturbations are nevertheless interesting because the dominant contribution to our peculiar motion could arise from perturbations with $\lambda >> 20$ Mpc and $(\delta\rho/\rho) << 1$ (cf. (4)).

The peculiar velocity induced at the boundary of a lump of scale λ and amplitude $\delta\rho/\rho$ actually depends on the value of Ω. The problem is discussed by Silk (1974), who presents graphs for V_{pec} more accurate than the crude relation (4), as a function of $\delta\rho/\rho$ for different choices of Ω. When $\lambda << \lambda_H$, our peculiar velocity will give a 24 hour X-ray anisotropy of amplitude

$$\left(\frac{\Delta I}{I}\right)_x = (3 + \alpha) \frac{V_{pec}}{c} \tag{9}$$

(when $\lambda \simeq \lambda_H$ the situation is more complicated because the sources of a substantial fraction of the X-ray background are themselves given a peculiar velocity: see below). The microwave background, if observations are made on the Rayleigh-Jeans portion of the spectrum ($\alpha = -2$), would yield

$$\left(\frac{\Delta I}{I}\right)_{mic} = \frac{V_{pec}}{c} \tag{10}$$

Comparison of (8) - (10) shows that these measurements yield an estimate of Ω: if the microwave background anisotropy is induced by inhomogeneities on scale λ ($\ll \lambda_H$), then the X-rays should show an effect $(3 + \alpha)$ times larger due to our motion (equation 9), and an effect due to the clumping of sources themselves which is larger by a factor $\sim x\Omega^{-1}$. In principle, therefore, comparison of X-ray and microwave data can yield constraints on Ω (Fabian and Warwick 1979): if Ω is very small the Galactic peculiar velocity of $\sim$ 600 km s^{-1} reported by Smoot et al. (1977) and Corey and Wilkinson (1976), and discussed by Smoot in these proceedings, could not be induced by a large-scale inhomogeneity on any scale between $\sim$ 100 Mpc and the Hubble distance, without the corresponding anisotropy in the X-ray source distribution exceeding what is observed.

Figure 3 shows the relative sensitivity of the microwave, X-ray and other limits in restricting the inhomogeneity of the universe on large scales. The amplitude of the inhomogeneities on a scale λ is expressed in terms of the present value of $(\delta\rho/\rho)$. The large scales (λ > 100 Mpc) would have grown since entering the horizon unimpeded by radiation pressure effects, so for them $(\delta\rho/\rho)$ is related to the curvature fluctuation by

$$\epsilon \simeq \left(\frac{\delta\rho}{\rho}\right) \left(\frac{\lambda}{\lambda_H}\right)^2 \tag{11}$$

(Note that Ω does not enter into this expression.) The upper limit on any 24 h component in the X-rays sets a limit shown as a line in Fig. 3. The peculiar velocity induced by the corresponding inhomogeneity shows up as an extra contribution depending on Ω.

We see from this diagram that X-ray isotropy observations with $\sim$ 1 per cent precision provide our best limits on the spectrum of inhomogeneities on scales between $\sim$ 100 Mpc and $\sim$ 1000 Mpc; on scales exceeding 1000 Mpc the most sensitive limits come from the microwave background - more specifically, from limits to the gravitational potential fluctuations around the surface of last scattering. On scales $\gtrsim \lambda_H$ other gravitational effects must be allowed for (cf. Rees and Sciama 1968; Dyer 1976).

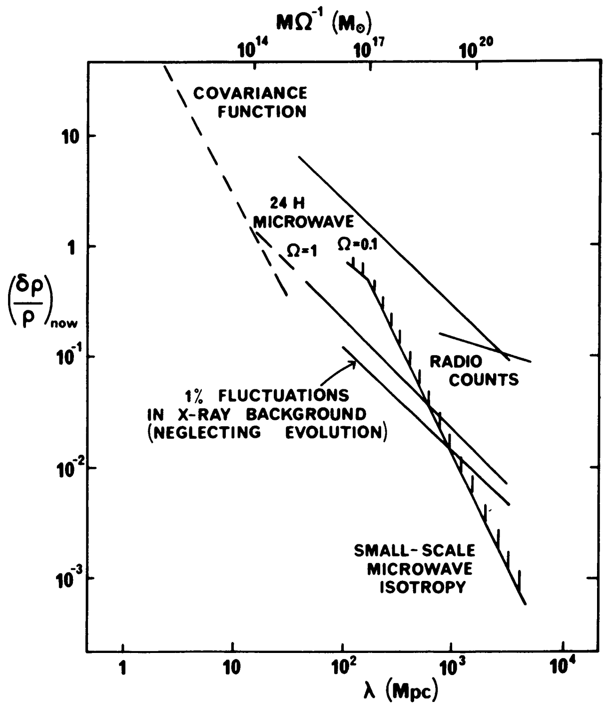

Figure 3. Constraints on density perturbations ($\delta\rho/\rho$) on various length scales λ exceeding ∿ 10 Mpc (adapted from Fabian et al. 1979). The lines labelled 'covariance function' and 'radio counts' assume that the galaxy and radio source distributions mimic the underlying mass distribution. The 'microwave velocity' lines give δv_G = 600 km s^{-1} and assume that we lie at the edge of such a perturbation. The radio count limits can perhaps be improved to 3 percent on scales of 1 Gpc, but depend upon the radio luminosity function etc. The microwave background observations imply upper limits to the Doppler and gravitational perturbations at the epoch of last scattering, and these yield approximately the limits indicated. Limits of ∿ 1 % on the isotropy of the X-ray background would yield, apart from an evolutionary correction (cf. equation 8), the line shown: note that this is potentially the most sensitive constraint on scales 100 - 1000 Mpc; on larger scales the microwave limits are likely to remain the best.

(The interpretation of the experimental limits to $\Delta T/T$ on smaller angular scales depends on the sharpness of the last scattering surface or 'cosmic photosphere', the influence of early reheating etc. However, these uncertainties do not enter on large scales, and on the smaller scales the X-ray limits may be better in any case.)

In compiling Figure 3, inhomogeneities of characteristic amplitude $(\delta\rho/\rho)$ were assumed to pervade the whole universe - $(\delta\rho/\rho)$ measures the amplitude of the Fourier components over a particular range of length scales. If, on the other hand, the universe contains isolated 'lumps' on large scales, embedded in a much smoother general background, then, as Fabian and Warwick (1979) have pointed out, there may be detectable consequences for the X-ray background, for observations with presently attainable sensitivity, even though the influence of the 'lump' may be undetectable as far as the microwave background is concerned. Of particular interest is the possibility that there may be isolated inhomogeneities on scales fully comparable with the observed part of the universe.

The naive discussion leading to (8) and (9) needs some modification for inhomogeneities with scales comparable with the Hubble radius λ_H ($\lambda \gtrsim 1000$ Mpc, say). A general treatment of cosmological models containing inhomogeneities on scales $\gtrsim \lambda_H$ would be prohibitively complicated. However, drastic simplifications ensue if we restrict attention to very small amplitudes - this is a justifiable restriction for observational cosmology because we know, from the microwave background, that the Universe is not far from being accurately "Robertson-Walker".

Provided that the curvature fluctuations are indeed small, we can consistently take a Friedmann model, with a certain overall curvature (or, equivalently, a well-defined mean density parameter Ω_o at the present epoch t_o). The nature of the fluctuations can then be specified by defining the density at each point (comoving coordinate r) as $\bar{\rho}(1 + \delta(\underline{r}, t))$; at each location $\underline{r}$, δ increases with t according to the standard expression for the growth of linear density perturbations in a Friedmann model of density parameter Ω_o. Under the restriction that $\delta << 1$, one can extend relation (4) for the peculiar velocity to the case $\lambda \simeq \lambda_H$. For an observer at the edge of a "Swiss cheese" perturbation one obtains

$$V_{pec} = \frac{\delta}{2} c \left(\frac{\lambda}{\lambda_H}\right) \Omega \left(\frac{2(1-\Omega)^{\frac{1}{2}} - 1}{2(1-\Omega)^{\frac{1}{2}} - \Omega}\right) \qquad (12)$$

The effect on the X-ray background can be analysed into three components;

(i) A 24h effect due to the enhanced density of sources in the 'lump'. (This effect would not exist if the lump lay beyond the redshift at which the X-ray background originates.)

(ii) A 24h effect due to our motion towards the 'lump'. (Reduced below (12) because the sources are themselves "falling" as well.)

(iii) A 12h quadrupole effect, with a minimum along the axis of symmetry towards the 'lump', due to the shear induced within the volume whence the bulk of the X-ray background originates (see Fig. 4 and caption).

Finally, we note that the X-ray background can set constraints on cosmological anisotropies on scales $\gg \lambda_H$ (Wolfe 1970).

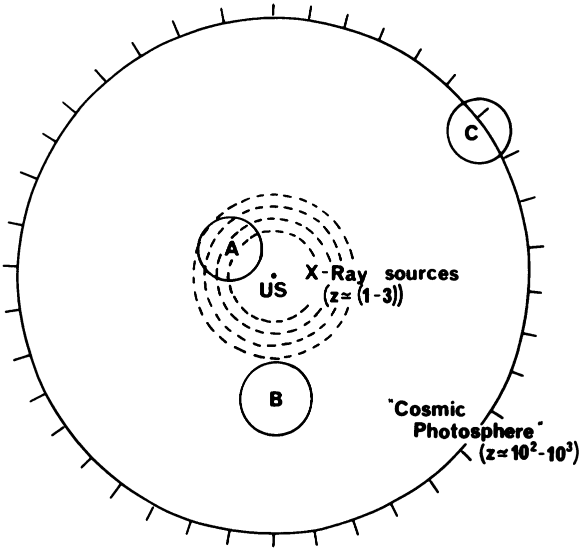

Figure 4. This diagram is intended to illustrate schematically the effect of a single isolated 'lump' of dimensions comparable with the Hubble radius, placed in various positions around us. The radial co-ordinate is the 'comoving r' of the Robertson-Walker metric; the 'cosmic photosphere' is assumed to be at $z \simeq 1000$, and the sources of the X-ray background at $z \lesssim 3$. (Note that, in terms of the coordinate r, $z \simeq 3$ is about half-way to $z \simeq 1000$ if $\Omega = 1$. If $\Omega < 1$ it is less than half way; moreover, volumes then increase faster than $\propto r^3$.) The effects on the X-ray and microwave background are as follows (cf. Fabian and Warwick 1979).

A. (i) 24h effects in microwave and X-ray backgrounds due to our peculiar motion. (ii) 12h effect of similar magnitude in X-ray background owing to shear induced by lump. (iii) 24h effect, Ω^{-1} times larger than others, due to excess sources in region of lump.

B. As compared with case A, effect (ii) is more important relative to (i); but (iii) is now absent because the lump lies beyond the X-ray sources.

C. There will in this case be a small 12h effect in the X-rays; our peculiar velocity shows up in the microwave background but not significantly in X-rays, since all the "sources" are falling at almost the same rate as us. The dominant effect, however, would be in the microwave background, due to the gravitational perturbation on the cosmic photosphere.

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DISCUSSION

Abell: Another way to place a limit on the scale of inhomogeneities is from the counts of numbers of galaxies, n, brighter than visual magnitude, m_V. The $n(m_V)$ curves found by Rainey (doctoral thesis, UCLA, 1977) in three widely separated directions in the sky are remarkably isotropic for $m_V > 16.5$. Rainey showed that inhomogeneities along the line of sight with density enhancements, $\Delta\rho/\rho \sim 0.5$ to 1, with a linear extent of 300 Mpc or greater would easily show up in his data in the magnitude range $16.5 \lesssim m_V \lesssim 19.5$, and can be ruled out. Incidentally, Peebles' power-law relation for the covariance function extends to about 20 Mpc (rather than 10 Mpc) if $H_o = 50$ km s^{-1} Mpc^{-1} (Peebles uses $H_o = 100$ km s^{-1} Mpc^{-1} for ease in comparison between various data sets).

Rees: These results are very interesting, but I suspect that the X-ray background isotropy limits will soon be substantially stronger (though these are admittedly not quite so unambiguous to interpret). As regards the covariance function, its value is unity for ~ 10 Mpc (taking $H_o = 50$ km s^{-1} Mpc^{-1}); I agree with you that its power-law form extends out to larger distances, as described in Groth's contribution.

Tyson: Faint number counts of galaxies suggest that there is a nearby supercluster of size 500 Mpc to 700 Mpc in the general direction of Virgo. More data from the south is needed to better define its angular extent.

In your schematic QSO model, perhaps we can learn something about the mechanisms at the bottom of your column by observing polarization in the X-rays, which would be caused by synchrotron radiation -- assuming the magnetic field there is not hopelessly tangled.

Rees: Such a discovery would be extremely interesting in this context. If it represented an "overdensity" of, say, 50%, then it would induce a peculiar velocity much larger than observed unless Ω were well below 0.1 (or unless the bulk of the matter were in some unclustered relativistic form). Such an effort -- if real -- ought to show up in radio source counts and in the X-ray background.

The magnetic field in the continuum-emitting region may be as strong as 10^3 to 10^4 gauss. The most important and direct evidence on physical conditions in this region comes from the studies of polarization variations at optical wavelengths, particularly by Roger Angel and his collaborators. I suspect that it will be a long time before the same thing can be done by the X-ray astronomers.

Margon: What are the chances that the X-ray spectrum of the "typical" high redshift QSO will prove to be no more complex than something that mimics a 45 keV exponential, thus allowing a simple superposition to explain the observed spectrum of the diffuse background?

Rees: Even if quasars do have a standard spectrum, there would still be a problem in accounting for the sharp bend in the background spectrum at 20 to 40 keV, particularly if one allows for the spread in redshift of the quasar contributing to the flux. Dr. De Zotti will be addressing this problem more fully in his paper.