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X-ray Astronomy and the IR Background

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Abstract. I review the recent Chandra results on the sources of the X-ray background and the X-ray properties of the SCUBA sources. We conclude that 10-20% of the IR background is produced by active galaxies and a similar fraction of the SCUBA sources harbor luminous AGN. Many of the Chandra sources are apparently luminous infrared galaxies themselves, but factors of 2–10 below the SCUBA limits. We summarize the X-ray evidence for metal production in groups and clusters and point out that these data require considerably more star formation than inferred from optical stellar data. The abundance ratios of Fe and Si indicate that much of the metals in groups and clusters was produced by massive stars, and the lack of evolution in Fe out to $z \sim 0.5$ argues for quite an early origin for the metals. This same process also seems to have injected considerable energy into the gas in groups and clusters, which may have dominated the mechanism of star formation and produced a metal-enriched intergalactic medium

1. Introduction

At this meeting we have seen extensive presentations of the measurement of the infrared background from 2–1000 μm and detailed calculations of its possible origin in processes related to star formation and active galaxies. For both of these mechanisms, recent results from X-ray astronomy are not only relevant but crucial. X-rays are an excellent way of detecting radiating massive black holes, otherwise known as active galaxies. With the recent considerable increase in sensitivity and angular resolution made possible by the launches in 1999 of Chandra and XMM-Newton, the new X-ray data can allow the detection of active galaxies at high redshift and hidden by large column densities of cold material. Since X-ray emission is an ubiquitous property of all classes of active galaxies, even those that show little if any signature in the near IR, optical and UV bands, X-ray measurements can determine which/how many of the luminous IR galaxies are AGN, a determination very difficult or impossible with far IR or optical data only.

Direct measurements of the sources of the X-ray background — essentially the sum over all the active black holes that ever existed — allow direct calculation of the contribution of AGN to the IR background (e.g., Almaini et al. 1999). That is, since Chandra and XMM provide an almost complete census of all active supermassive black holes, infrared follow-up observations of these objects can directly determine the contribution of active galaxies to the infrared background. Infrared and X-ray astronomy are also extremely compatible. High energy X-ray emission can essentially "see" through the dust and gas which enshrouds the central object, while IR astronomy detects the re-radiated emission absorbed by the same dust and gas. Thus, as is becoming clear, hard X-ray and IR surveys can detect many more objects than IR and UV surveys and essentially detect the same objects. In fact, the so-called unified active galaxy models predict that there should be a direct correlation between the X-ray column density, which determines how much absorption there is, the X-ray luminosity, which is a measure of the intrinsic luminosity of the AGN, and the IR luminosity, which represents the same radiation reprocessed by dust and gas in the thermal flux.

Recent theoretical (e.g., Davé et al. 2000) and observational results (e.g., Fukugita, Hogan, & Peebles 1998) show that most of the visible baryons in the universe exist in a hot, $T > 10^{6.5}$ K, phase in groups and clusters of galaxies, and most of the theoretically predicted baryons lie in a hot, $T > 10^{5.5}$ K, phase in the IGM. X-ray imaging spectroscopy of the clusters and groups (e.g., Mushotzky et al. 1996) shows that most of the metals ever created lie in this hot gas. Thus, determination of the metallicity, distribution and redshift evolution of this gas is a direct measure of the cosmic metal formation rate, as opposed to the stars, which contain a considerably smaller fraction of all the metals. Since we now believe that much of the metal formation in the universe occurs in dust enshrouded objects that produce the infrared background, there is a direct connection between the X-ray measurements in the clusters and groups and the theoretical framework of the origin of the IR background.

2. Active Galaxies, the X-ray Background and the IR Background

The X-ray background is primarily produced by large numbers of X-ray luminous point sources at cosmological distances. Before Chandra, detailed models of the X-ray background (e.g., Comastri et al. 1995) showed that a new class of object was required to explain both the flux, source counts and spectral shape of the background. This class of object was identified as highly absorbed active galaxies. The general idea is that the very flat spectrum of the X-ray background could be extremely well modeled by summing up the contribution from active galaxies that had a wide range of line of sight column densities, from 10^{21-24} atoms cm^{-2}, and that evolved with redshift in just the right way. The required space density for these active galaxies was extremely high, more than 1000 objects per square degree, about 10 times larger than the highest density ever seen in deep optical color surveys. Because they would have high column densities, it was clear that the view to the central engine would be "blocked" in the UV- optical bands, and thus these objects would be difficult to recognize with optical imaging or spectroscopy. Clear examples of such objects are seen in the nearby universe, with perhaps the most famous being the IR luminous galaxies NGC 6240 (Iwasawa & Comastri 1998b) and NGC 4945 (Madejski et al. 2000). While both of these are luminous hard X-ray sources, neither of them shows classical active galaxy signatures in the optical or even the near IR (Lutz et al. 1996) band.

The radiation emitted in the rest-frame soft X-ray to optical bands should be absorbed by the intervening dust and gas, and, presumably, re-radiated in the infrared bands. Thus, there would be a direct connection between the sources of the X-ray background and potential sources of the infrared background. Unfortunately, the modeling of the X-ray background was sufficiently flexible (e.g., Gunn and Shanks 1999) that a wide variety of models that fit the X-ray background gave very different predictions for the infrared flux and flux distribution.

Chandra and XMM-Newton have the requisite sensitivity, reaching limits of roughly 2×10^{-15} ergs cm^{-2} sec^{-1} in the 2–10 keV band in exposures of 100 ksec, to detect these highly absorbed objects even at high redshift. For example, at $z = 5$ with $\Omega = 0.2$, $\Lambda = 0.8$, $h = 0.65$, Chandra can detect a source in a 100 ksec observation (similar to our deep field discussed below) with a luminosity in the 2–10 keV band of 1.8×10^{44} erg sec^{-1}, roughly equal to the luminosity of the classical nearby Seyfert galaxy NGC 5548 and about 100 times less luminous than the prototypical quasar 3C 273. At $z = 3$ a column density of 10^{23} atoms cm^{-2} (corresponding to $A(V) \sim 45$) reduces the Chandra flux by only 60%, and at $z = 5$ by 50%. Broadly similar to the IR, there is a "negative K correction" for absorbed sources in the X-ray band since the signature of photoelectric absorption gets redshifted to lower energies. For example, the count rate for a source with $N(H) = 10^{24}$ atoms cm^{-2} and a power law spectrum with energy index of -0.7 drops by only ~ 5 from redshift 1 to redshift 3. The $M \sim 10^{7-8} \mathrm{M}_{\odot}$ massive black holes (MBHs) expected to form at high z in cold dark matter scenarios (Haiman & Loeb 1999) can be detected by Chandra at $z \sim 5$ even if they are radiating at only $0.1 - 0.01$ of the Eddington limit and have high column densities.

As usual in astronomy, the answer to what are the objects which produce the X-ray background lay in direct observation. With the advent of Chandra, X-ray astronomy acquired the angular resolution and sensitivity to detect the sources of the X-ray background and provide accurate enough positions to search for optical, radio and IR counterparts (Mushotzky et al. 2000; Barger et al. 2000). Our results are based, primarily, on one field, the SSA13 field, with a total solid angle of ~ 90 square arc minutes, for which we have published the results of a 100 ksec observation. These early Chandra results have shown that the optical counterparts of the majority of the Chandra sources are very faint ($\sim 1/3$ are fainter than $I = 23.5$), show little, if any, sign of nuclear activity in high signal to noise Keck spectra, and have much of the optical emission dominated by starlight. All the objects but one with $I < 23.5$ have redshifts that range from 0.1 to 3.4. Their X-ray luminosities range from $3 \times 10^{41} - 10^{45}$ ergs sec^{-1}, which corresponds to the full range of luminosities seen in the local volume of the universe, indicating a very broad luminosity function. It is clear that most of the fainter objects do not have strong optical or UV emission lines.

As predicted by the models of the X-ray background, the Chandra sources outnumber "regular" active galaxies by a factor of 5–10. The mean colors of these objects can be rather red, with $I - K \sim 2 - 5$. Many of these objects also show indications of absorption in their X-ray spectra, with median column densities between 3×10^{22} and 3×10^{23}. If the ratio of reddening to column density in the optical-IR band is similar to that in the Milky Way, this gives $A(V) \sim 13 - 130$, effectively extinguishing all of the UV-near IR band. Most

($\sim$ 80%) of these objects are detected at a flux threshold of 25 μJy in an ultradeep 1.4 GHz radio observation. These data also allow a validation of the X-ray source positions, since the rms difference between the X-ray and radio positions is only 0.4 arcsec. The ratio of radio to X-ray flux indicates that these objects are radio quiet, suggesting that the radio emission, most likely, does not originate in the active nucleus.

Almost all of the identified optical counterparts are luminous galaxies, with $\sim$ 10% of all the luminous galaxies in the field containing Chandra sources. Since we now assume that most luminous galaxies contain massive black holes, this indicates that the duty cycle for the black holes to radiate is $\sim$ 10%, or a lifetime of $\sim 1 - 2$ Gyr. While this is considerably shorter than the Salpeter timescale, these sources are radiating at much below the Eddington luminosity. Using simple scaling between the total optical luminosity and black hole mass, the bolometric luminosity of these objects implies an Eddington ratio which can range from 4×10^{-6} to 0.1. If we assume that the Chandra sources are accreting black holes, radiating with 10% efficiency, we can transform the Chandra source counts into a volume density of black holes by using the mean correction factor of 20 between the X-ray and bolometric luminosity. We find a mean density of black holes of $\sim 4.8 \times 10^5\,[(1 + z_f)/3]\,\mathrm{M}_\odot\,\mathrm{Mpc}^{-3}$ (where I have set z_f, the mean distance of the objects, to $z_f \sim 2$). This is remarkably close to the mean density of black holes of $5 \times 10^5\,\mathrm{M}_\odot\,\mathrm{Mpc}^{-3}$ measured by the recent HST teams using a relationship of black hole mass to galaxy velocity dispersion (Gebhardt et al. 2000; Merritt & Ferrarese 2000). This indicates that, given the errors in our simple assumptions, the Chandra data detect essentially all the black holes in massive bulges that ever existed, completely consistent with the idea that the sum of the X-ray radiation from massive black holes makes up the X-ray background. While there still may be objects missed by Chandra, especially at $z < 1$ where high column densities reduce the Chandra flux considerably, they cannot make a major contribution either to the 0.5–10 keV background or to the total mass of black holes. Thus, Chandra provides the finding chart for assigning a classification to the IR sources detected in Chandra fields; basically, if Chandra detects the object it is an active galaxy; if not detected by Chandra, it is a star forming system (of course rapidly star forming galaxies are also X-ray sources, but they have a much lower ratio of X-ray to IR flux (by about 15) than active galaxies do).

If we assume that these objects follow the relationship between FIR luminosity and radio flux for "normal" galaxies, then we can predict the infrared luminosities. We find that $\sim 2/3$ of these objects would be classified as luminous IR galaxies, $L(\mathrm{FIR}) > 10^{12}\ \mathrm{L}\odot$, and a few would be in the ULIRG class. Only 2 of the Chandra sources are detected by SCUBA, and only one of these is in the complete X-ray sample of Barger et al. Barger et al. use these observations to estimate the contribution of the detected Chandra sources to the 850 μm background and find that $\sim$ 10% of the flux comes from these objects. Since we have resolved > 60% of the X-ray background at the present Chandra flux limits, this value may increase by at most a factor of 2. We thus may say with some confidence that hard X-ray sources, alias the total population of active galaxies, contribute roughly 10-20% of the FIR background radiation. Recently (after the end of this Symposium), Krabbe et al. (2000) found a linear scaling between the

$8-13\,\mu$m and X-ray fluxes of both active galaxies and starbursts; the active galaxies have a factor of ~ 15 higher X-ray/IR ratio. Using this scaling relation, the Chandra sources with a flux between $(2-10)\times 10^{-15}$ ergs cm^{-2} sec^{-1} should have an $8-13\,\mu$m flux of $30-150\,\mu$Jy, which is reachable by IRAC on SIRTF. Thus, SIRTF observations of the Chandra sources will be able to directly test the results discussed above. Thus, in broad detail, Chandra has confirmed the ideas of the X-ray background models: the sources tend to show large column densities and can be luminous infrared sources. However, the optical counterparts are not at all like classical active galaxies and represent more than 75% of all active galaxies.

3. SCUBA Sources

Thus, while we have answered the statistical question of how much of the IR background is associated with active galaxies, we have not answered the detailed question of whether the SCUBA sources themselves are, in general, active galaxies. Using the radio to FIR correlation we find that most of the Chandra sources should lie a factor of $\sim 2-10$ below the SCUBA sensitivity threshold. Indeed, there are only 2 detections of Chandra sources by SCUBA in the 13 hour field, and thus, in general, the Chandra sources are not SCUBA sources.

So what about the SCUBA sources themselves? Only 2/12 of the SCUBA sources in the SSA13 field are detected by Chandra. Combing the results for our field with the results from the A370 field (Bautz et al. 2000), as well as the HDF (Hornschiemer et al. 2000) and other fields (Fabian et al. 2000) one finds that most (25/32) of the SCUBA sources are not detected by Chandra, but $\sim 20\%$ are and are thus luminous AGN. The best examples are in the A370 field; for example, in SMM J02399-0136 and 02399-0134 (Bautz et al. 2000)), the AGN is very luminous and is a major contributor to the total bolometric luminosity (with $\sim 40\%$ of the total energy). As pointed out by Bautz et al., some of the Chandra fields were not deep enough to constrain the AGN contribution of the SCUBA sources, and thus some of the early conclusions were premature (Severgnini et al. 2000). The Chandra data indicate that most of the SCUBA sources are powered either by star formation or by an AGN that is so deeply buried that even Chandra cannot detect it. It is clear that such buried objects exist, e.g., the Compton thick Seyfert IIs. These results are in general agreement with the models developed by Almaini et al. and Gunn & Shanks. About 10–20% of the SCUBA sources correspond to regions containing luminous AGN. In fact, to quote from Bautz et al., $20^{+30}_{-16}\,\%$ of submillimeter sources exhibit X-ray emission from AGN (90% confidence), consistent with expectations of their contribution to the diffuse X-ray background. This fraction is consistent with the ratio seen for all luminous galaxies, indicating that we may again have a duty cycle issue. In other words, since the fraction of SCUBA sources that are AGN is consistent with that seen in other luminous galaxies, we do not yet know, statistically, if the high far IR luminosity is related to the presence of an AGN.

The Chandra X-ray spectrum of one of the SCUBA sources is consistent with a very high column density, and its overall spectral energy distribution is indeed similar to that of NGC 6240. Thus, it is almost impossible to use standard diagnostics in the rest frame UV, optical or $1-20\,\mu$m band to determine which, if any, of the luminous $850\,\mu$m sources are AGN.

4. Metals in the Universe

It has been over 20 years (Serlemitsos et al. 1977) since iron was discovered in the intergalactic medium that fills the space between the galaxies in clusters. Since then, Fe abundances have been measured out to redshifts of ~ 0.5 and Fe and Si abundances have been accurately determined in more than 100 clusters (Mushotzky & Loewenstein 1997; Fukazawa et al. 1998). Theoretical work (White et al. 1993) shows that clusters should be "fair samples of the universe". That is, there is no known mechanism for concentrating baryons in clusters and that, to first order, the composition of clusters (e.g., gas, galaxies, metals, dark matter) should be representative of the universe as a whole. It is also clear that galaxies are open systems, with galactic winds able to eject large amounts of material from them (Heckman 2000). Mergers and infall of material may have important effects on their composition. Thus, if one wants to derive a cosmic census of heavy element formation in the universe (e.g., metals), clusters and groups are the most representative and unbiased sample. With the advent of XMM-Newton and Chandra, accurate Fe abundances can be measured out to redshifts of ~ 1 and Si abundances to $\sim 1/2$.

The derivation of the abundance in the IGM in clusters is straightforward. Since the electron temperature is high ($kT > 2\,\mathrm{keV}$), one observes the He and H-like transitions in the 0.3–7 keV band from all the abundant elements (C, N, O, Ne, Mg, Si, S, Ca, Ar, Fe and Ni), whose atomic physics is relatively simple and well known. The electron temperature is determined by the shape of the continuum, and the line strengths can be directly transformed into abundances. In groups, where the electron temperature is less than 2 keV, the emission is dominated by the Fe L-shell complex, for which the atomic physics is not quite so accurate. However, the Si and S abundances for these systems should still be reliable.

One of the main discoveries of X-ray astronomy is that most of the baryons in clusters and groups lie in the hot, X-ray emitting gas. Roughly speaking, for a massive cluster the gas has 3–10 times more mass than in the galaxies. Since the mean metallicity of the gas is $\sim$1/3 solar, very similar to the mean metallicity of the stars in the galaxies in the cluster, this means that most of the metals are in the gas phase. If indeed clusters are fair samples of the universe, as argued above, this means that tracing the abundance and distribution of the metals by measuring starlight misses most of the metals and incorrectly locates them. This was realized after the first results of the ASCA satellite. Mushotzky & Loewenstein (1996) compared the metal production inferred from the X-ray spectra of clusters with that determined from the UV light from galaxies (Madau et al. 1996), and calculated that the UV data were missing roughly 2/3 of all metal creation. Mushotzky & Loewenstein predicted that there must be a large amount of metal production which was invisible to UV detectors, and speculated that heavily dust-obscured objects may be the site of much of the metal creation. We know these today as the ultraluminous infrared galaxies and the SCUBA sources.

The relatively low gas content and the low abundances in groups indicates that groups tend to have a low ratio of metals to starlight (the metal mass to light ratio of Renzini et al. 1993). Since almost all theories of metal formation and stellar evolution indicate that there should be roughly equal amounts of metals formed per unit optical light (for a reasonable range of stellar initial mass functions, Loewenstein & Mushotzky 1996), this is relatively hard to understand. One possible explanation is that much of the processed gas is ejected by galactic winds (David et al. 1991). This requires about 1 keV of energy per particle, which is consistent with that required in models of cluster evolution. If the ejection idea is correct, most of the metals created in the stars which reside in groups should be in an ionized intergalactic medium. Simple calculations (Davis et al. 1999) indicate that the IGM would be enriched to > 0.04 solar by such a process. The large amount of required energy should have a strong effect on the X-ray surface brightness profile, the gas temperature and the evolution of groups. All of these effects, to a greater or lesser extent, have been seen (Lloyd-Davies et al. 2000; Loewenstein 2000). The magnitude of the observed effects is roughly consistent with that derived from semi-analytic models of galaxy formation in which feedback from star formation is taken into account. In these models, over 70% of all baryons either never collapse into or are ejected from galaxies (Somerville & Primack 1999). As discussed at this meeting, these semi-analytic models are "tuned" to produce the galaxies as we see them.

Thus, the X-ray observations of groups have the potential for radically changing our view of the universe, from one in which most metals live in stars and gravity totally dominates at all scales, into one in which energy injection processes such as supernovae and quasars have an important role and most of the metals in the universe are in the IGM. These results essentially imply that large scale structure, metal formation, and tracing of the baryonic universe require X-ray data. It seems likely that Chandra and XMM-Newton will strongly test these ideas.

The relative abundance of the elements is a strong guide to the processes that created them. In particular, this applies to the ratios of the "α" elements — those created by rapid burning of oxygen and produced in massive stars — including O, Ne, Mg, and Si, which are produced primarily by type II supernovae, and S, Ar, Ca, and Fe, which can be produced by both type I and type II supernovae (Loewenstein & Mushotzky 1996; Gibson et al. 1997). The data (e.g., Fukazawa et al. 2000) show a relatively high Si/Fe ratio in massive clusters, dropping to lower levels for groups. These overall trends are consistent with $\sim 0.2 - 0.5$ of the Fe being produced by type I SNe and the rest by type IIs, and with most of the Si being produced by type IIs. The total abundance patterns seem to require a higher type II to type I ratio than seen in the Milky Way. This is consistent with the idea that much of the metals in the universe is produced in the IR luminous starburst galaxies, which should be dominated by type II SNe. The measurement of oxygen abundances for massive clusters from XMM is eagerly awaited, since oxygen is produced solely by massive stars. Combining the Fe, Si and O abundances will allow not only discrimination between type I and type II supernovae, but also allow inferences about the initial mass function to be made.

There is no evidence for evolution in the cluster Fe abundance out to redshifts of ~ 0.5 (Mushotzky & Loewenstein 1997) or perhaps $z \sim 0.8$ (Donahue et al. 1999). There is no sign of the large amounts of massive star formation in the HST images of clusters out to redshift of ~ 0.8 that would be required to produce the observed metals in the gas. The combination of the X-ray and optical data thus indicates that the metals in the cluster gas were created at redshifts > 1.2 (this is derived by adding the observed look back time to the clusters with the main sequence lifetime of the luminous O and B stars). Thus the X-ray cluster data argue that most of the energy radiated by the objects which formed the metals in clusters originates at high redshift.

5. The "Extra" Energy Problem

Detailed observations of clusters and groups are in general agreement with detailed numerical simulations (Eke et al. 1998). Roughly speaking, clusters forming in a hierarchical dark matter dominated universe, have the properties that are predicted by numerical simulations. However, there are two major disagreements: the entropy per particle (Ponman, Cannon, & Navarro 1999 — hereafter PCN), and the gas distribution in groups.

As first noted by PCN, groups have considerably more entropy per particle than predicted by the numerical simulations. Detailed theoretical work by several groups have confirmed this (e.g., Loewenstein 2000) and indicate that about 1 keV of energy per particle is required. Thus, either some process to inject extra heat other than gravity, or, alternatively, some process to increase the entropy of the gas relative to that in the Eke et al. simulations, must have been at work. Similarly, groups have considerably more extended X-ray surface brightness distributions than clusters, also consistent with the injection of extra heat (White 1991). This same process can also produce the deviation of the X-ray luminosity vs. temperature relation from the theoretically predicted slope of 2 to the observed slope of ~ 3. Recent calculations show that this amount of extra heat is required to "fine tune" the semi-analytic models of galaxy formation, as discussed above.

Loewenstein (2000) has shown that it is possible to produce this extra heat from supernova and stellar winds, but it requires very efficient thermalization of the supernova energy. If this is true, most galaxies would have, during their rapid star forming periods, blown enormous galactic winds, and much of the total material created by nucleosynthesis would have been expelled into the intergalactic medium. The injection of extra energy allows good agreement between the observed cluster luminosity function and theoretical calculations, a serious problem in most numerical calculations.

In addition, the same indication of energy injection is seen in spiral galaxies (Pen 1999). In most hierarchical clustering theories, dark matter potential wells either have the average baryon density of the universe or have concentrated their baryons. Detailed simulations and measurement show that these baryons are not apparent, and therefore must have been driven off from spiral and elliptical galaxies.

Since the binding energy of the most massive galaxies is ~ 1 keV per particle, it is clear that if this energy is produced in the stars that lived in galaxies, the whole process of galaxy and group formation and evolution must have been strongly affected by non-gravitational processes. Recent calculations by Valageas & Silk (1999) and others indicate that there is not enough energy in supernovae to produce the extra energy required, and these authors imply that only quasars could produce the needed energy. However, it is difficult to understand the exact mechanism responsible. Also, as pointed out by Pen (1999), most numerical calculations of the formation and evolution of large scale structure would overproduce the observed soft X-ray background via emission from the gas in groups. If this is true, the same sort of mechanism is required to drive the gas out of the group potential wells and thus reduce the soft X-ray emission from groups. However, the calculations by Davé et al. (2000) do not find this effect, and thus the jury is still out. If this mechanism indeed is at work, gas will end up in the intergalactic medium, heat it and enrich it in metals.

6. Conclusion

We anticipate an exciting next few years. SIRTF and perhaps ISO data should be able to measure the IR flux of the faint Chandra sources and directly test the results from the Chandra deep surveys. Detailed comparisons of X-ray and IR spectroscopy of ultra-luminous infrared galaxies and SCUBA sources will allow an accurate estimate of the contribution of AGN to the IR background. XMM-Newton and Chandra will measure the chemical abundance of clusters out to $z \sim 1$ (or even higher redshift should such objects exist) and look for the signs of the first epoch of metal injection into the IGM.

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Discussion

Bernard Pagel: There is actually no discrepancy between the mass of stars today according to Fukugita, Hogan, & Peebles (1998). A Salpeter IMF (as truncated by them at the low end) gives a cosmic metallicity of order 0.3 $Z_\odot$ in the IGM, assuming $\Omega_{IGM} \sim \Omega_{baryons}$.

Richard Mushotzky: I assume that Professor Pagel has already accommodated the fact that most metals are in the hot phase of the IGM! What he says is true, if, as I have assumed, clusters are fair samples of the universe. Another way of saying this is that we "know" that the Saltpeter IMF is correct and we "know" the metal production from such an IMF. Using the observed total amount of starlight then gives a total metal production which is sufficient to create a 0.3 solar metallicity for all of the cosmic baryons! Thus, we should have predicted that the cluster gas should be metal enriched and so should the IGM.

Jim Felten: This relates to the previous (Pagel's) comment. You are making the implicit assumption that the metallicity in a rich cluster arises from activity within the cluster – a closed box. We could argue details of that, but let's assume it's true. Then what do the observed metallicities say about the parameter Δx – the fraction of hydrogen processed through stars? After all, you also measure the total hydrogen in your hot gas (the correction for additional baryons in the galaxies is small), so your data can be used to calculate Δx.

Mushotzky: Basically one can just take the observed abundances relative to solar. That is, we measure abundances relative to hydrogen and so the answer is just the relative abundance.