I. Historical Introduction and General Characteristics of the CXB.

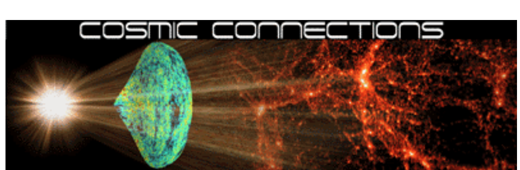
Historical Introduction

* The "birth" of the field of X-ray astronomy is usually associated with the flight of a particular rocket experiment in 1962 that yielded the detection of the first non-solar cosmic X-ray source: Scorpius X-1. (Giacconi et al. 1962)

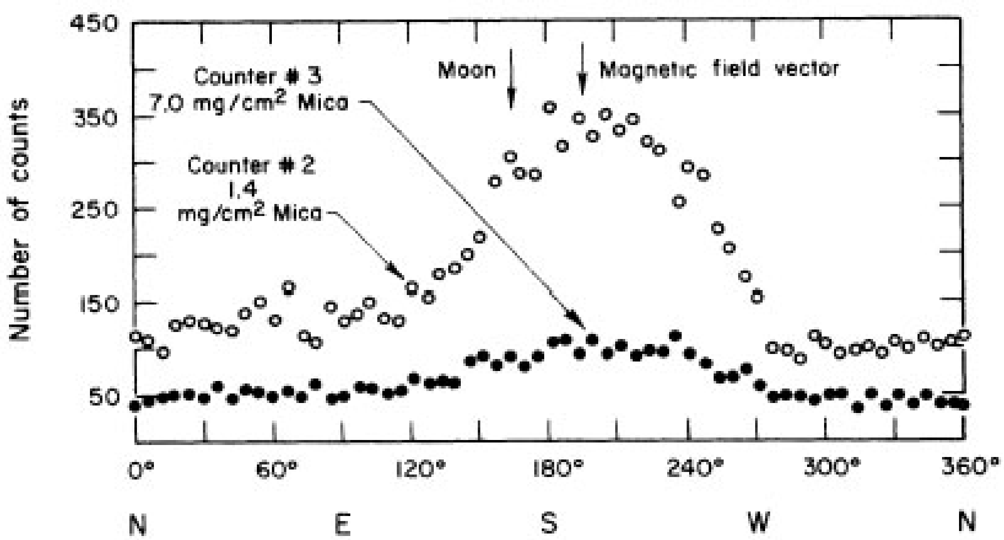
* That same rocket experiment also yielded the discovery of an apparent diffuse component of X-radiation, the Cosmic X-ray Background (CXB). (N.B. This was well in advance of the discovery of the Cosmic Microwave Background by Pensias and Wilson!)

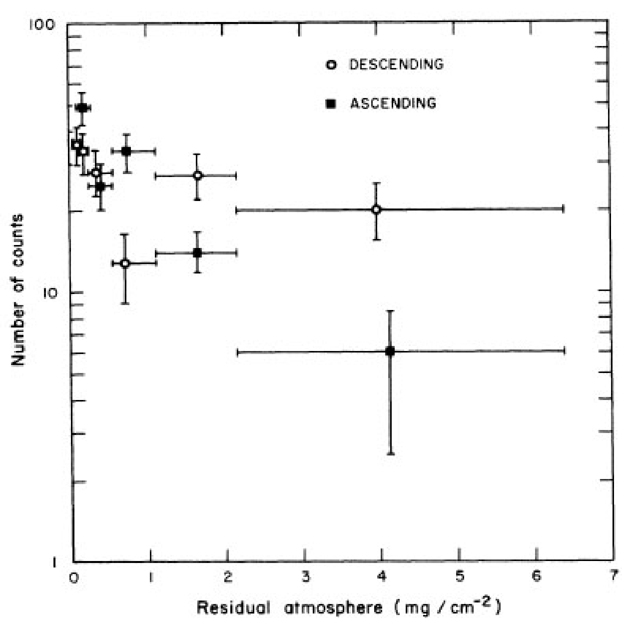
* In the ensuing 40 some odd years, our understanding of the X-ray Universe has progressed considerably. X-rays have now been detected from virtually all classes of astronomical systems, ranging from normal stars to the most distant galaxies.

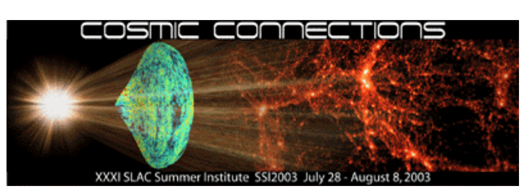
* Nevertheless, the precise origin of the CXB remains puzzling. This has been one of the great mysteries of high energy astrophysics!



Historical Introduction







Historical Introduction

PHYSICAL REVIEW LETTERS

VOLUME 9 DECEMBER 1, 1962 NUMBER 11

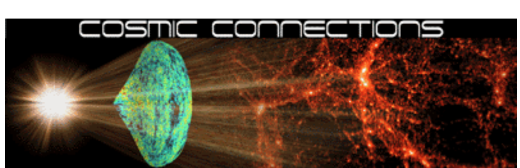
EVIDENCE FOR X RAYS FROM SOURCES OUTSIDE THE SOLAR SYSTEM*

Riccardo Giacconi, Herbert Gursky, and Frank R. Paolini
American Science and Engineering, Inc., Cambridge, Massachusetts

and

Bruno B. Rossi
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received October 12, 1962)

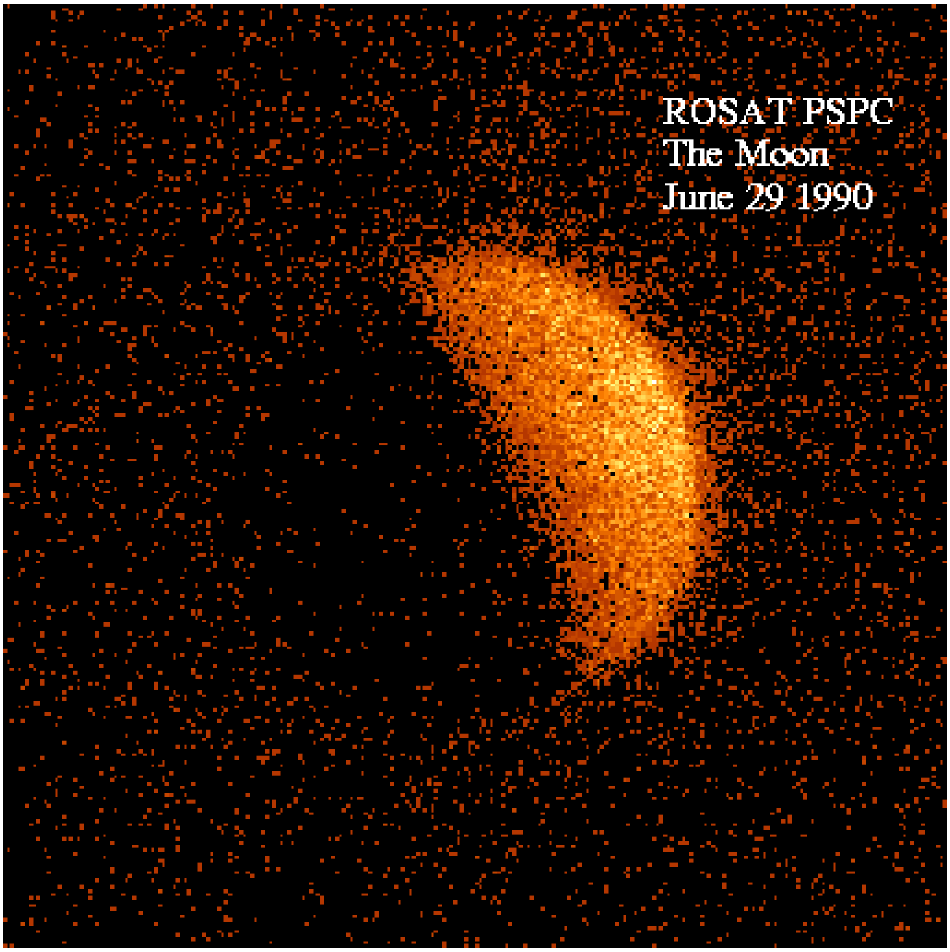
* "The diffuse character of the observed background radiation does not permit a positive determination of its nature and origin. However, the apparent absorption coefficient in mica and the altitude dependence is consistent with radiation of about the same wavelength responsible for the peak. Assuming the source lies close to the axis of the detectors, one obtains the intensity of the X-ray background as 1.7 photons cm^{-2} s^{-1} sr^{-1} and of the secondary maximum (between 102^o and 18^o) as 0.6 photons cm^{-2} s^{-1}. In addition, there seems to be a hard component to the background of about 0.5 photons cm^{-2} s^{-1} sr^{-1} which does not show an altitude dependence and which is not eliminated by the anti-coincidence."



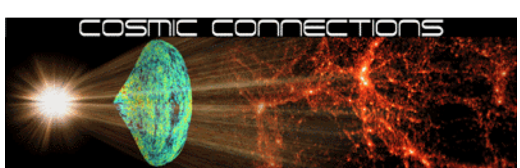
Historical Introduction

2002 Nobel Prize in Physics Awarded to Riccardo Giacconi for the Discovery of X-ray Emission from Celestial Sources.

Historical Introduction



* Giacconi et al. were originally searching for fluorescence of solar X-rays from the Moon. This was finally detected by the ROSAT experiment in 1990. This picture also shows that the dark side of the Moon occults the diffuse background - the first unambiguous demonstration that the CXB is coming from outside the solar system!



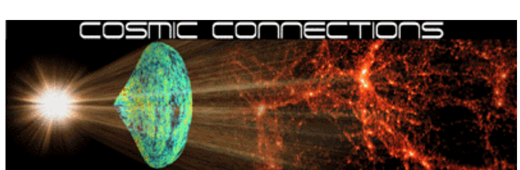
General Characteristics of the CXB

* The CXB represents a distinct peak in the overall background spectrum, second only in prominence to the CMB.

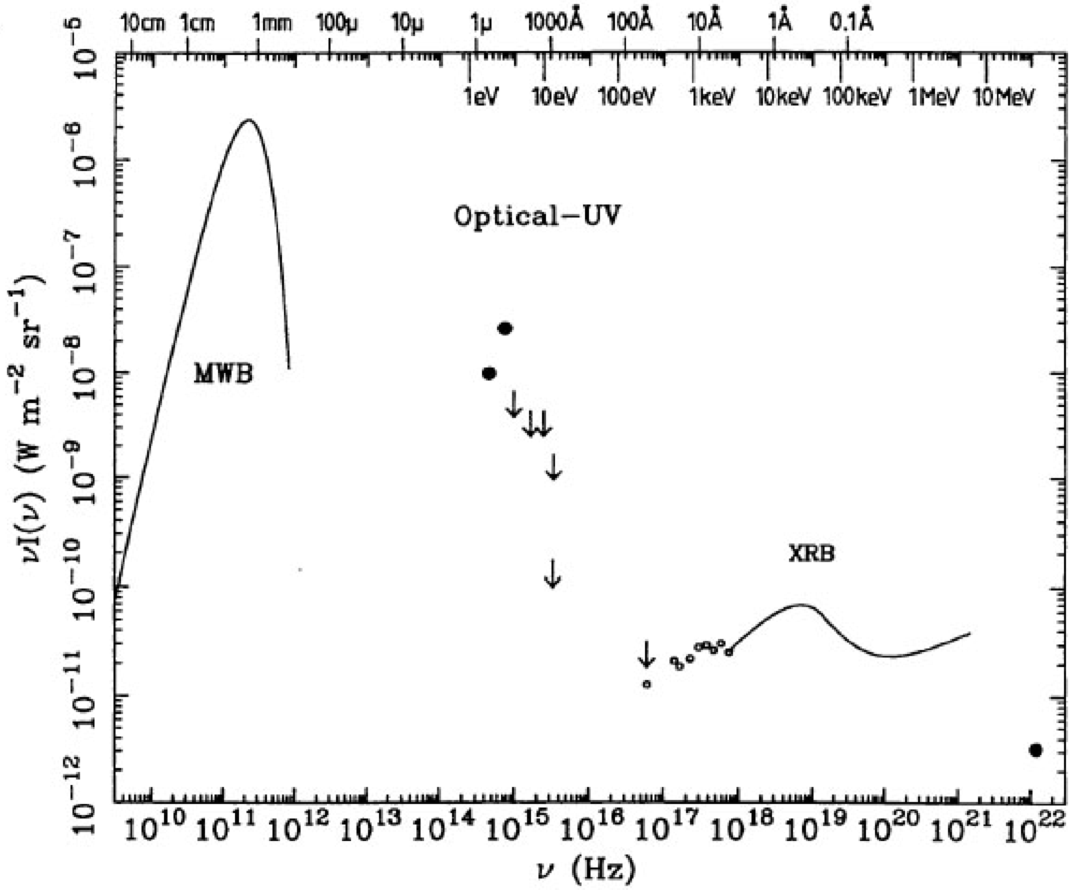
* It spans roughly four decades in energy, 100 eV to 1 MeV. This is a wider band logarithmically than the IR/Opt/UV.

* The integrated energy density is roughly 10% that of the CMB, indicating that its generation plays an important role in the total energy budget of the Universe.

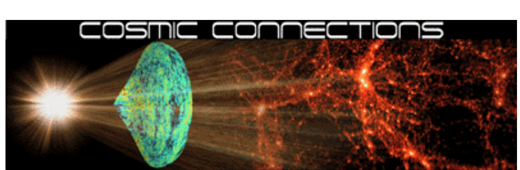
* In contrast to the situation in longer wavelength bands, measurement of the CXB is relatively free from complications. There are no contributions due to scattering of starlight in the solar system or the galaxy. However, there is a definite galactic contribution, especially at the lower energy band of the spectrum.



General Characteristics of the CXB



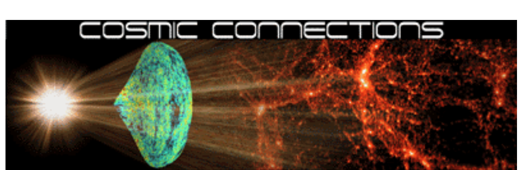
From Fabian & Barcons, 1992, ARAA, 30, 429.



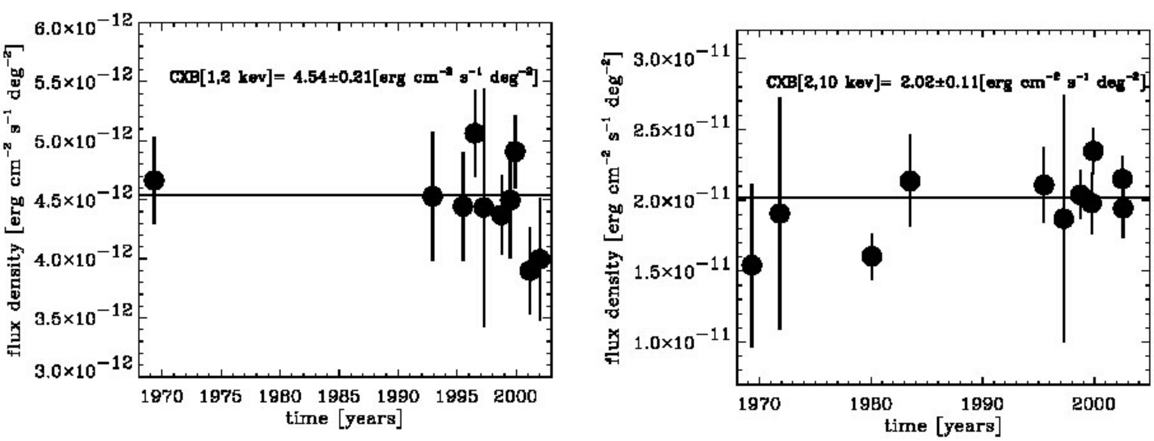
General Characteristics of the CXB

- * Absolute Intensity:
  - The absolute intensity of the CXB is hard to measure accurately due to the difficulty of definitively screening out non-X-ray events.
  - At low X-ray energies, solar electrons can be especially problematic, introducing a time-dependent background which is not easily predictable.
  - At hard X-ray and soft gamma-ray energies, cosmic ray activation of the spacecraft and experiment housing becomes and issue.
  - These give rise to 20 -30% systematic uncertainties in the absolute intensity, as gleaned from a comparison of the various measurements of the years.
  - Current best guess:

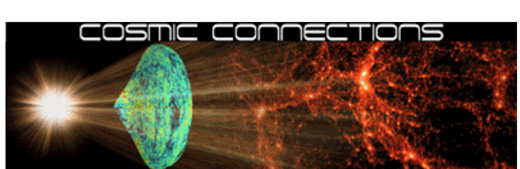
$$I\ (1\ \mathrm{keV}) \sim 10\ \mathrm{photons\ cm^{-2}\ s^{-1}\ sr^{-1}\ keV^{-1}}$$



General Characteristics of the CXB

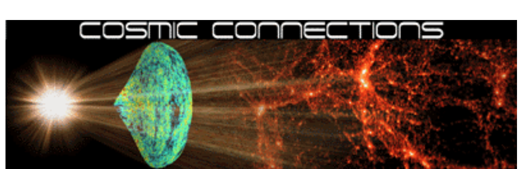


From Moretti, Campana, Lazzati, and Tagliaferri, 2003, Ap. J., 588, 696.

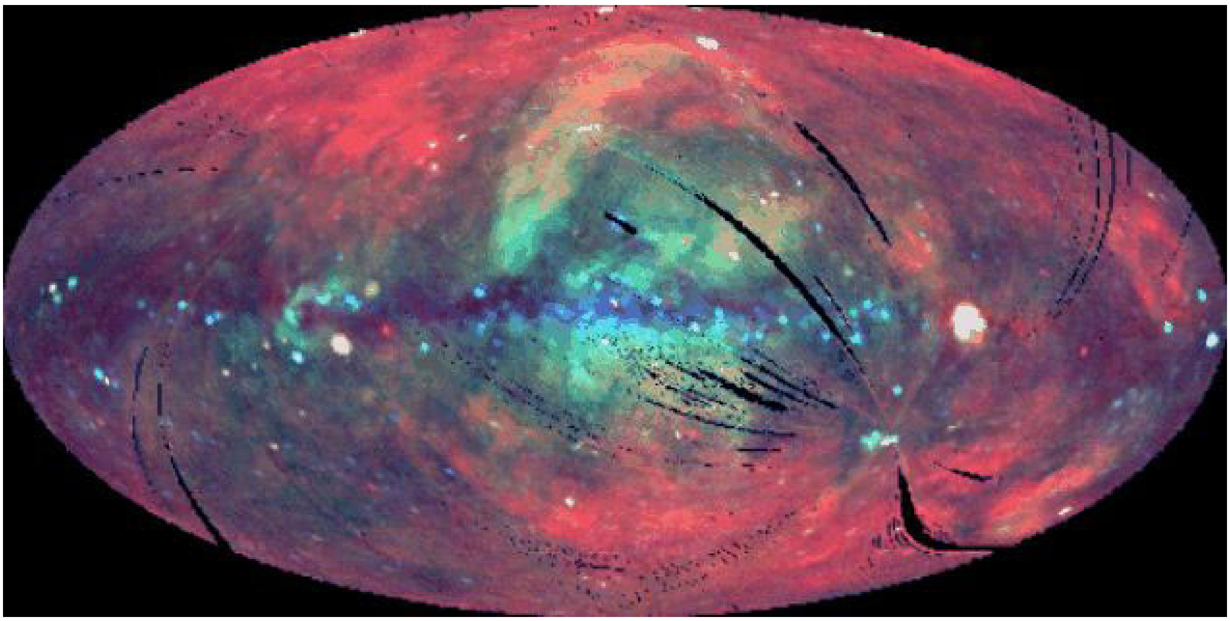


General Characteristics of the CXB

* Anisotropy:
  – The diffuse CXB looks quite different in different energy bands.
  – In "soft" X-rays, E = 0.1 - 1 keV, there is a clear correlation with galactic latitude. This means that background is strongly affected by emission and/or absorption in the interstellar medium of the Milky Way. (We'll return to this in Lecture II.)
  – In "hard" X-rays, E = 3 - 300 keV, the emission is remarkably uniform across the sky, except for a narrow "ridge" of emission in the plane of the galaxy. This provides the primary evidence that the bulk of the CXB is extragalactic in origin.
  – The situation is less clear in the MeV band because it becomes difficult to filter out time-dependent instrumental backgrounds. However, at high gamma-ray energies, E > 100 MeV, there is a strong contribution from cosmic ray interactions with matter and photons in the interstellar medium. The emission correlates well with interstellar hydrogen column density in this band.

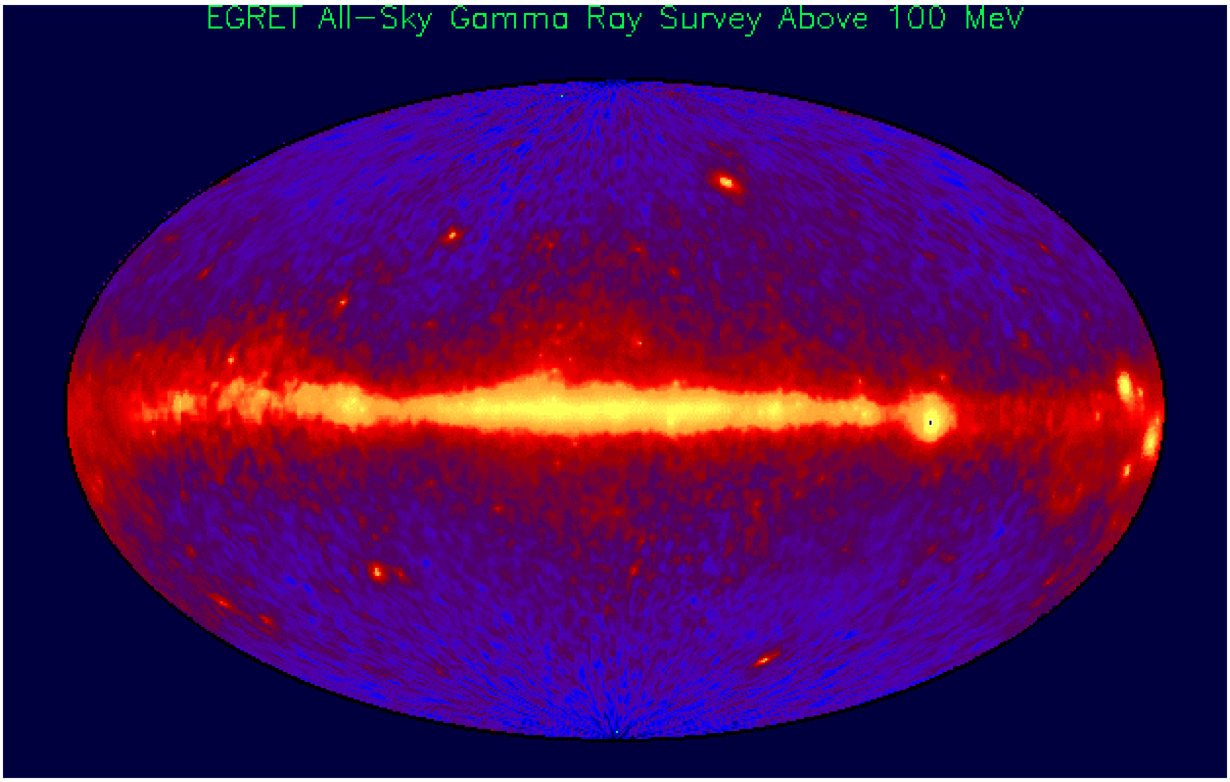


General Characteristics of the CXB

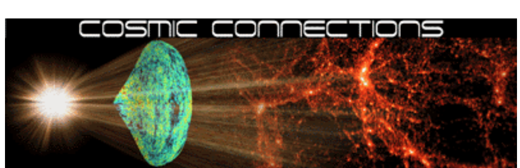


ROSAT Image of the X-Ray Sky.

General Characteristics of the CXB



EGRET Image of the Gamma-Ray Sky



General Characteristics of the CXB

* Anisotropy (Cont'd):
  – For the hard X-ray band, the intensity is highly isotropic over the sky. However, there is a small residual dipole term associated with the proper motion of the Local Group with respect to the distant Universe. The effect is $\delta I/I \sim 5\%$, and the direction is close to the direction of the dipole in the CMB, although it is not well-determined.

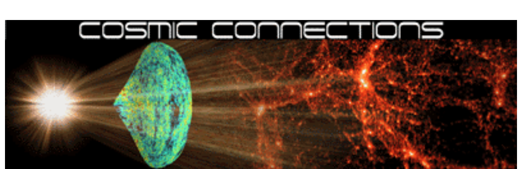
The dipole pattern results from two separate, but related effects:

(1) The so-called "Compton-Getting" effect, due to the motion of an observer in an isotropic radiation field.

– I_ν/ν^3 is proportional to the photon phase space density and is thus invariant. If I_ν is proportional to $\nu^{-\alpha}$, then $I'_{\nu'}/I_{\nu'}$ is proportional to $(\nu'/\nu)^{3+\alpha}$. This gives $\delta I/I \sim (3+\alpha)v/c$. The inferred velocity is $v \sim 475 \pm 165$ km s^{-1}. The CMB gives $v \sim 360$ km s^{-1}.

(2) The likelihood that the sources of the gravitational field responsible for the proper motion of the Local Group are correlated with the sources of X-ray emission. The expected direction of the dipole vector is the same.

The fact that the dipole is indeed detected with the correct direction provides further proof that the CXB is associated with a distant extragalactic source!



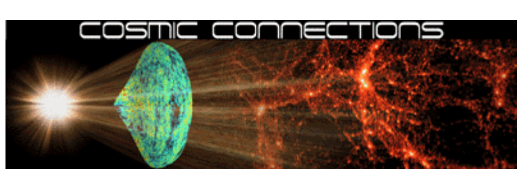
General Characteristics of the CXB

* Spectrum:
  - The spectrum of the CXB is again different in different energy bands.
  - At soft X-ray energies, there are clear indications of thermal emission from hot gas with a characteristic temperature $T \sim 10^6$ K ~ 0.1 keV. This is probably associated with the interstellar medium or the halo of the Local Group.
  - In the hard X-ray band, the spectrum is given by:

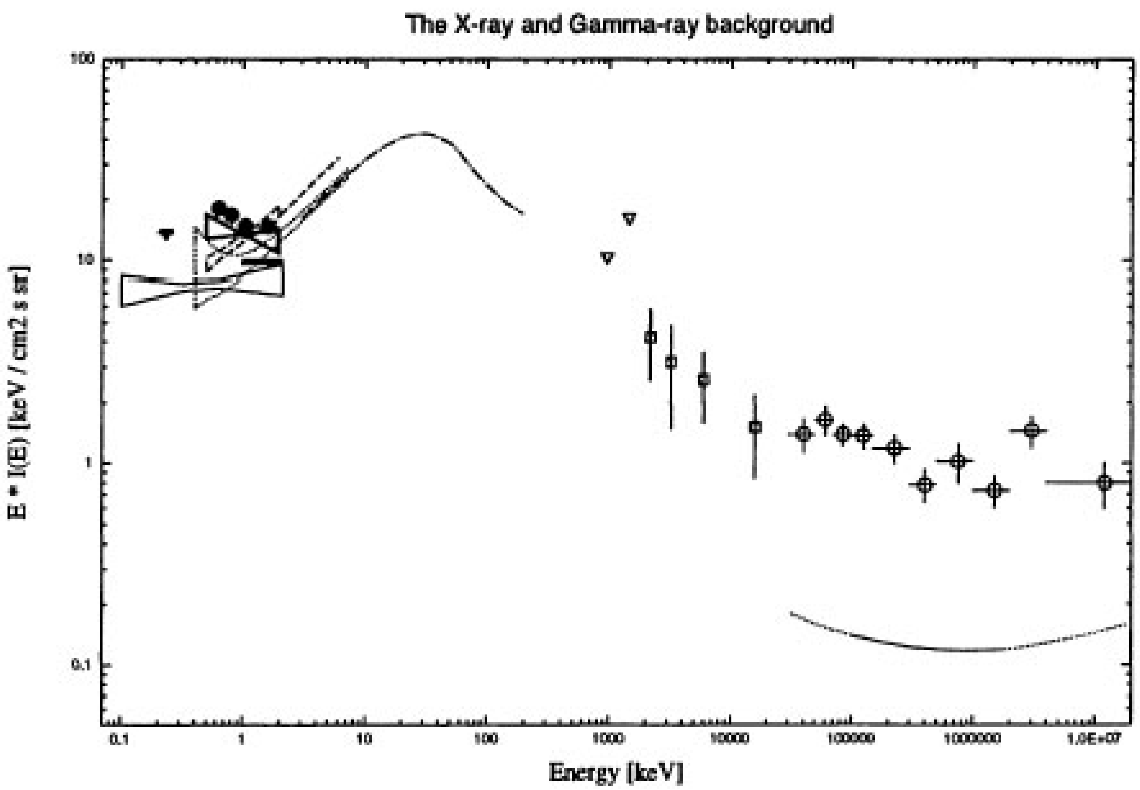
$$I(E) = 7.9\, E^{-0.29} \exp[-E/41.1\ \mathrm{keV}]\ \mathrm{keV\ cm^{-2}\ s^{-1}\ sr^{-1}\ keV^{-1}}$$

    This is remarkably close to the spectrum associated with thermal bremsstrahlung radiation with a temperature ~ 40 keV. (More on this later!)

  - In the gamma-ray band, the spectrum "breaks" into multiple power law components. For a while, there was thought to be a "30 MeV bump" that excited a lot of interest, but that has now been shown to have been an artifact of improper subtraction of instumental backgrounds.



General Characteristics of the CXB



From Hasinger, 1996, A&ASS, 120, 607.

II. Contributions to the CXB from Discrete X-Ray Sources.

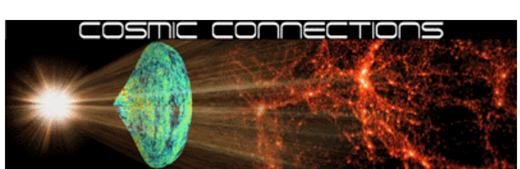
Discrete Source Contributions

* Prior to the launch of the *Einstein Observatory* in 1978, nearly all X-ray astronomy experiments incorporated simple, collimated proportional counters without focussing optics.

* The characteristic fields of view were $\sim 0.5^{o}$ or greater. Discrete sources were detected as local excesses as these experiments scanned across the sky. The sensitivity was limited by source confusion.

* Nevertheless, during this era, hundreds of sources were detected. Mostly, these were bright X-ray binary sources in our own Galaxy. However, a few extragalactic sources, bright nearby active galactic nuclei and clusters of galaxies, were also discovered.

* To estimate the contribution of such discrete extragalactic sources to the CXB, one had to estimate their “luminosity function” and then try to extrapolate out to larger distances.



Discrete Source Contributions

* One means of evaluating the discrete source contribution is via a "Log N - Log S" analysis - the number of sources detected as a function of their flux, S.

* For a uniform population in a Euclidean universe, S is proportional to d^{-2}, while N is proportional to d^3. This gives $dN/dS \propto S^{-5/2}$, or $N(>S) \propto S^{-3/2}$. A slope very close to -1.5 was indeed observed for the early samples.

* However, the slope must flatten out at very faint fluxes due to the cosmic expansion and the fact that we are looking back in time. (Solution to Olbers' Paradox.)

* Such a flattening was indeed inferred from a *fluctuations analysis*. Assuming the sources are randomly distributed, one can predict the expected statistical fluctuations from field to field for a given Log N - Log S relationship. If the $S^{-3/2}$ line is extended down until the integrated intensity matches the CXB intensity, the predicted fluctuations would have been higher than observed.

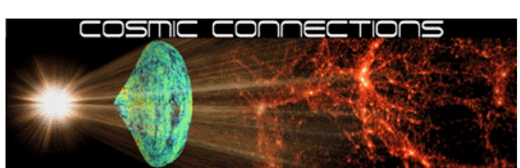
Discrete Source Contributions

* Log N - Log S alone therefore does not allow us to estimate the contributions that individual source populations make to the unresolved X-ray background.

* To go further, we need to take account of the *evolution* of the luminosity function with cosmic time.

* One means of evaluating this is via a "V/V_{max} test". For each source, calculate the volume of space internal to that source distance, divided by the volume of space in which that source could have been detected given the sensitivity of the instrument. If there is no evolution in either the luminosity distribution or the density of the source population, the distribution in V/V_{max} will be uniform.

* "Negative evolution" corresponds to an excess in low values of V/V_{max} (sources are less numerous and/or less dense at higher z.) "Positive evolution" corresponds to an excess at higher values of V/V_{max}.



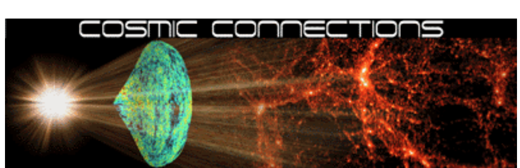
Discrete Source Contributions

* The bright extragalactic source sample detected with non-imaging experiments was divided roughly equally between clusters of galaxies and active galactic nuclei (AGNs).

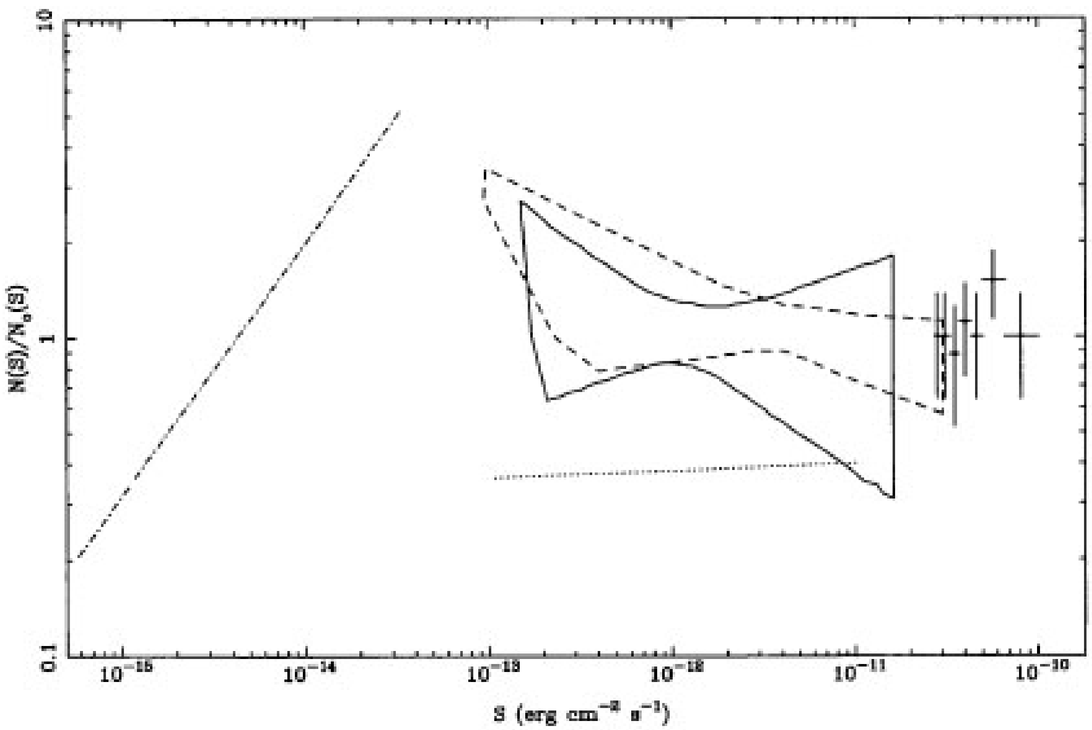
* However, clusters were found to exhibit negative evolution, while the AGNs exhibited strongly positive evolution. This was the first indication that AGNs might be responsible for the CXB.

* Still, the uncertainties were sizeable given the limited statistics. Many analyses relied on trying to calibrate L_X/L_{opt} ratios for AGNs, and then using the much better statistics of optical AGN samples to predict the evolution. This was prone to a number of systematic biases and other forms of selection effects.

* The net conclusion from this work was that discrete sources (mostly AGNs) account for at least ~ 30% of the CXB, but one could not rule out the presence of a significant truly diffuse component.



Discrete Source Contributions



Log N - Log S inferred from source counts and fluctuation analyses in the 2 - 20 keV band, normalized to the $S^{-5/2}$ Euclidean curve. (From Butcher et al. 1997, MNRAS, 291, 437.)

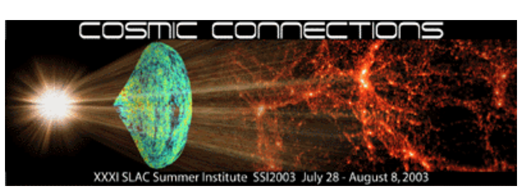
Discrete Source Contributions

* The situation changed dramatically with the flight of the first true X-ray telescopes on satellite experiments.

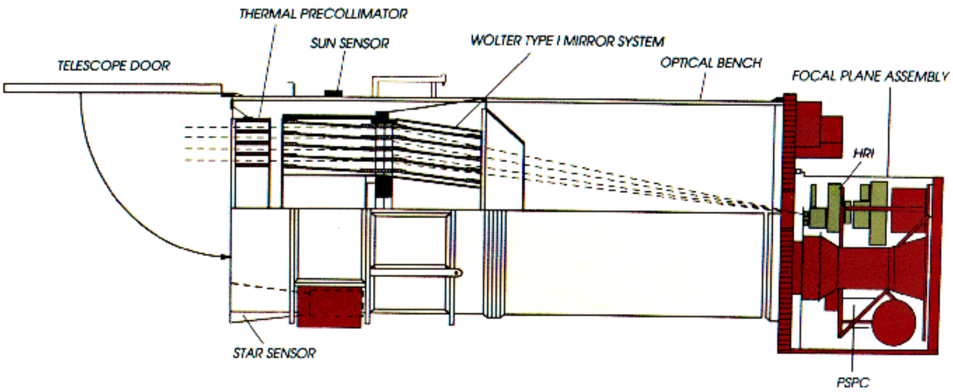
* The U.S. *Einstein Observatory* was launched in 1978, and the German *ROSAT Observatory* was launched in 1990. These missions yielded few arc-sec resolution for the first time.

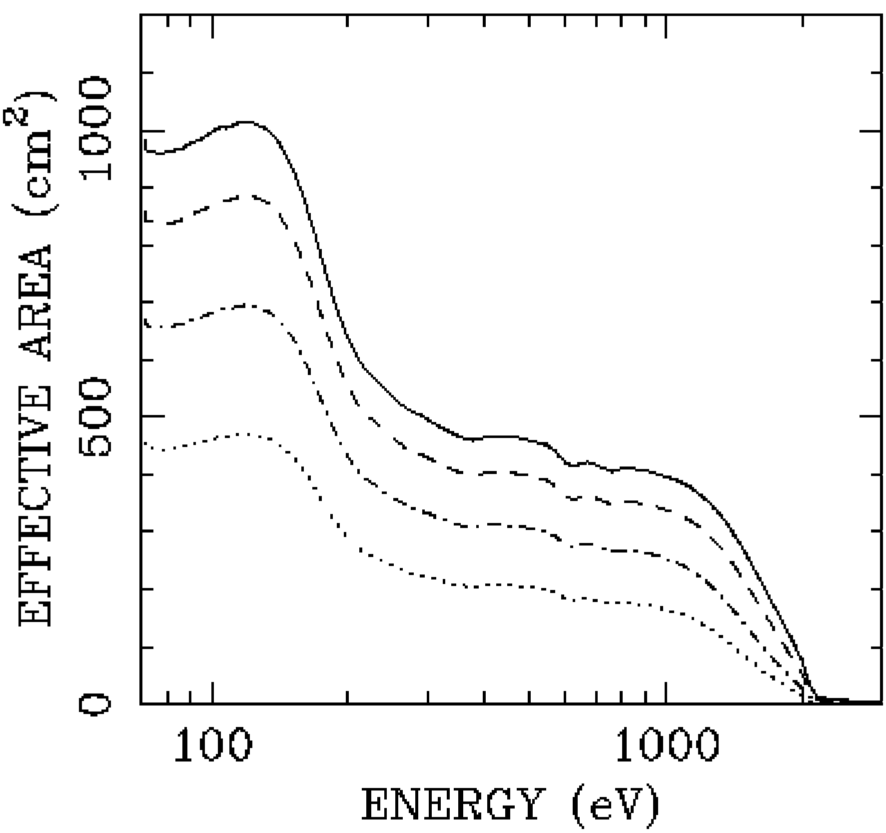
* In the X-ray band, the real part of the index of refraction is slightly less than unity: $n = 1 - \delta$, with $\delta << 1$. Focussing is achieved via *total external reflection* off polished surfaces at small graze angles. To make a true imaging lens, two bounces are required. The size of the aperture is thus related to the maximum graze angle, γ: $d \sim 2f \tan(4\gamma)$, where f is the focal length.

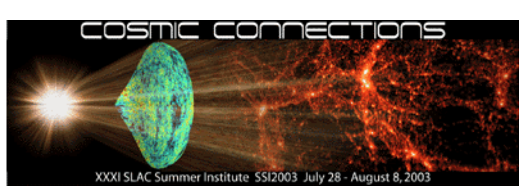
* But the critical graze angle for total external reflection is proportional to E^{-1}. So one can only get sizeable apertures for the softest X-rays.



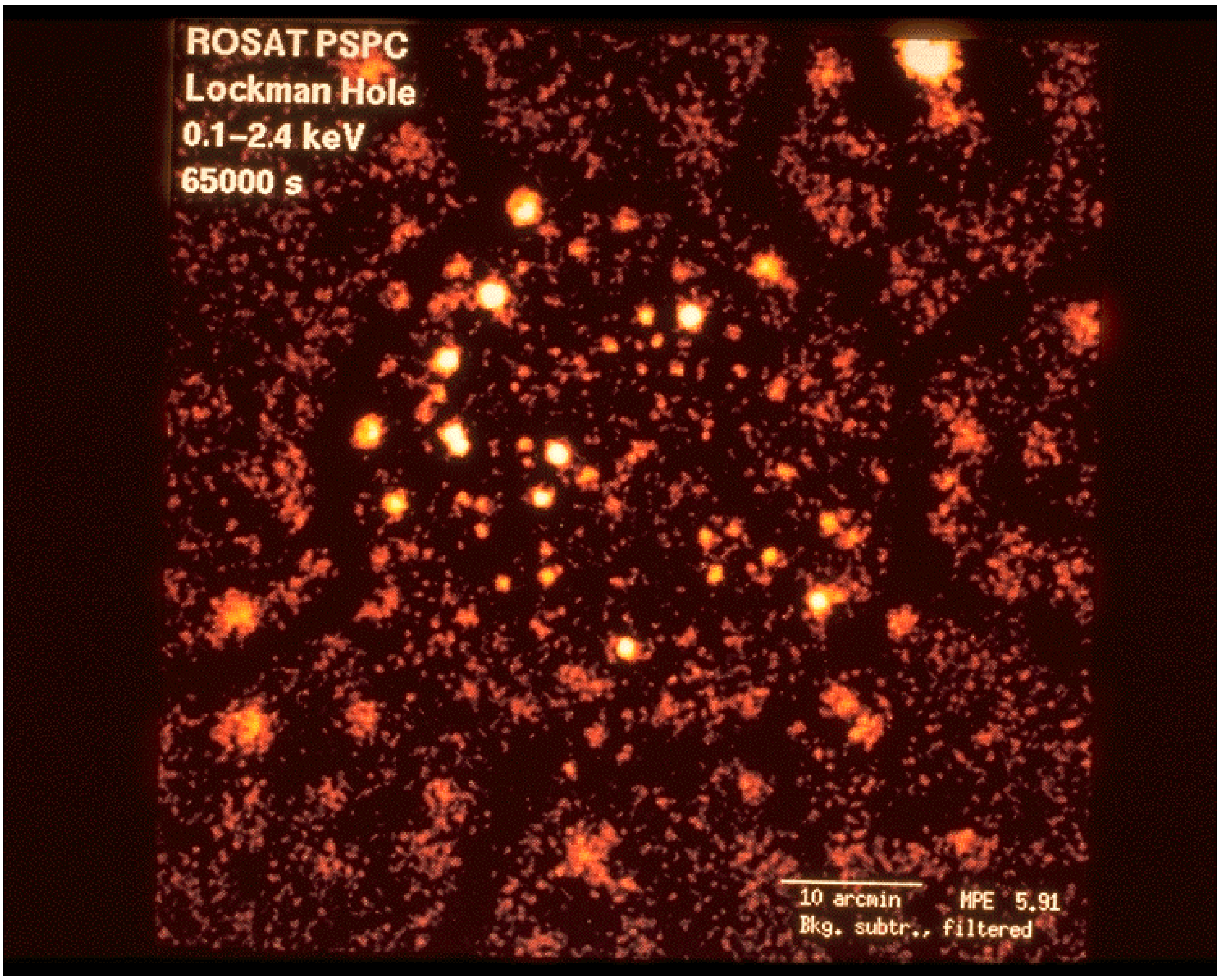
Discrete Source Contributions







Discrete Source Contributions



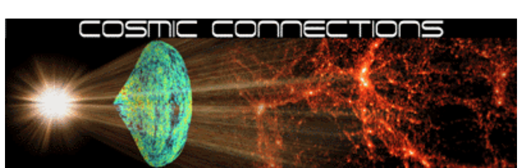
Discrete Source Contributions

* Deep ROSAT images of the sky determined that > 80% of the CXB at soft X-ray energies (~ 1 keV) is attributable to discrete sources. Mostly these are bright AGNs.

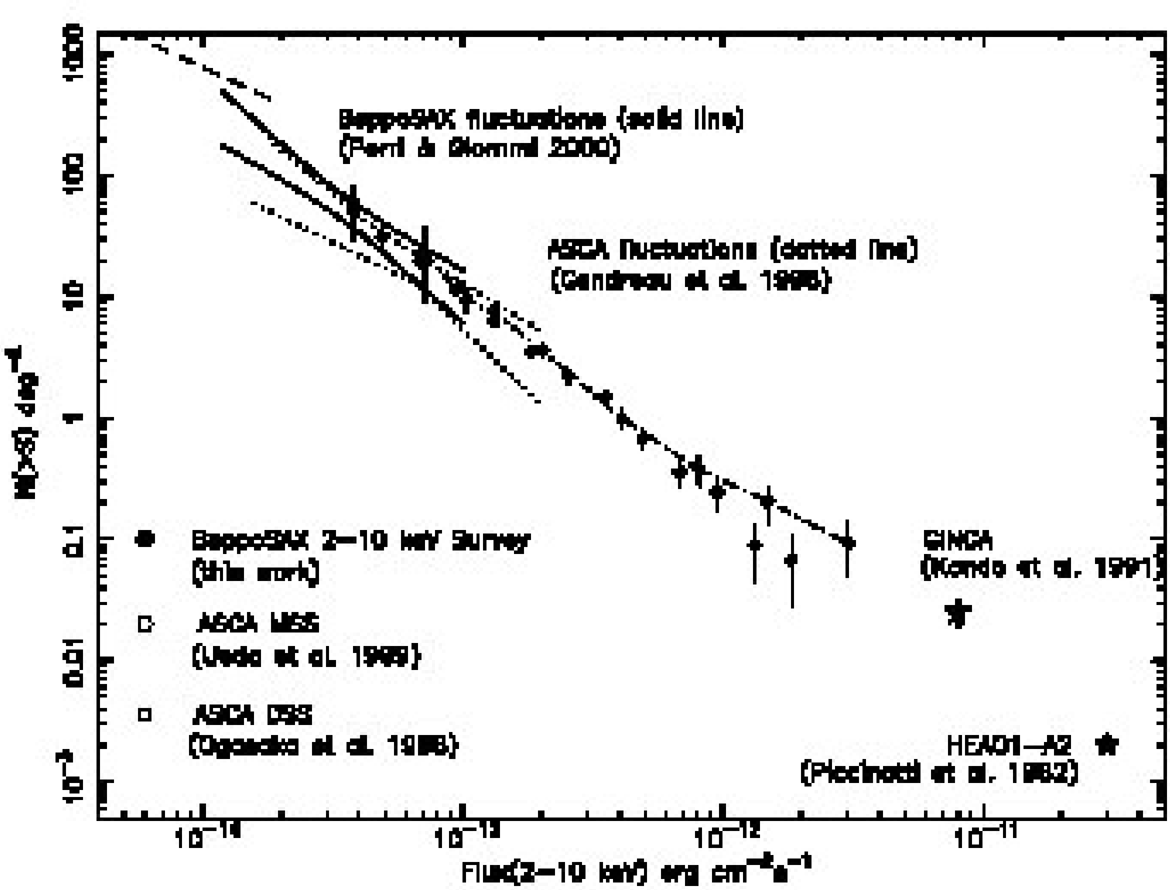
* However, it was unclear how to extrapolate this result to higher energies (~ 30 keV) where the bulk of the energy density is.

* The *ASCA Observatory* and the *BeppoSAX Observatory* incorporated much more densely nested mirrors, yielding larger aperture at smaller graze angles and thus higher energies. However, the angular resolution of these experiments was still much too coarse to resolve most of the background.

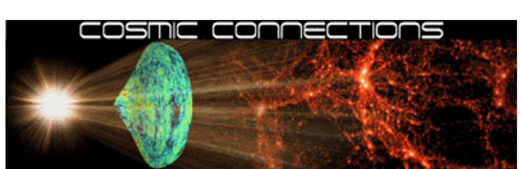
* Nevertheless, the fluctuation analysis indicates that the curve flattens at faint source fluxes. The implication is that the angular space density of the sources responsible for the bulk of the CXB must be much higher than can be extrapolated from the bright AGN sample. A new population is required.



Discrete Source Contributions



Constraints on the Log N - Log S relation in the 2 - 10 keV band from the fluctuations analyses on the ASCA and BeppoSAX surveys (From Giommi et al. 2000, A&A, 362, 799.)



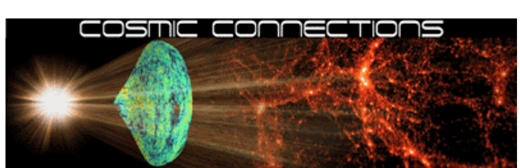
Discrete Source Contributions

* The final clarification of the discrete character of the CXB has come only fairly recently with the launch of the *Chandra Observatory* in June 1999.

* *Chandra* incorporated a magnificent 0.5 arc-second X-ray telescope with a 10 m focal length, thereby providing an over two order-of-magnitude improvement in sensitivity for point source detection out to 10 keV.

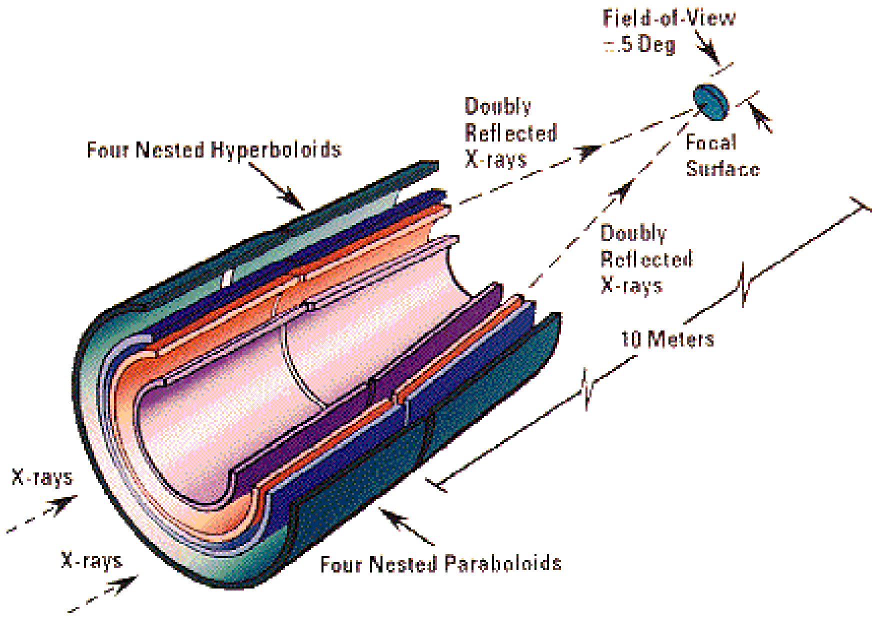
* Extended "deep surveys" with *Chandra* have unambiguously determined that > 90% of the CXB at soft X-ray energies (0.5 - 2 keV), and > 80% of the CXB at hard X-ray energies (2 - 8 keV) is indeed due to discrete sources. The principal residual uncertainty is not in the source population but in the overall normalization of the background.

* The very faint sources detected are different in character than the bright AGNs detected in less sensitive surveys. They are a mix of luminous infrared starburst galaxies, optically faint X-ray sources, and high-to-extreme redshift AGNs.

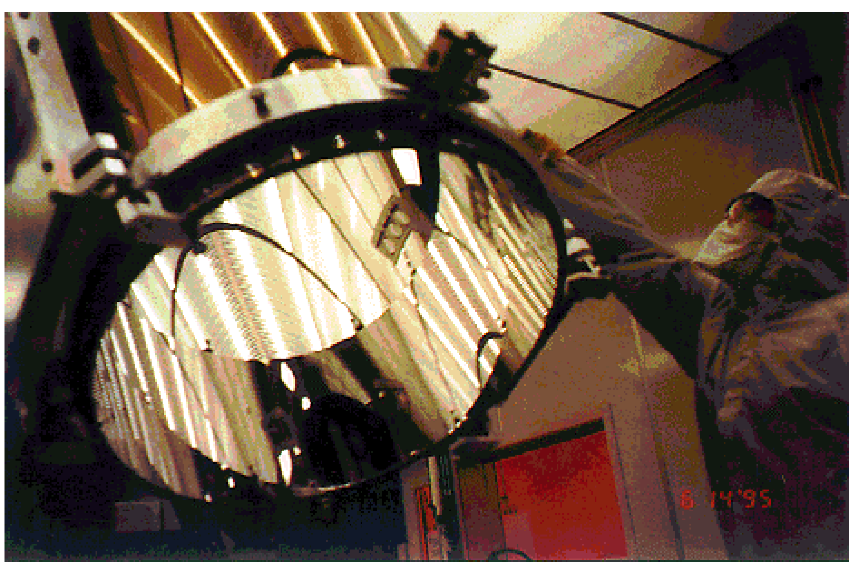


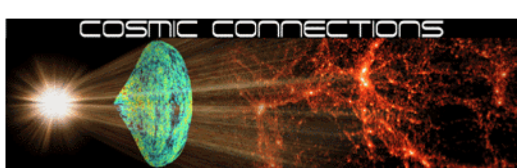
Discrete Source Populations

Discrete Source Contributions



Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter





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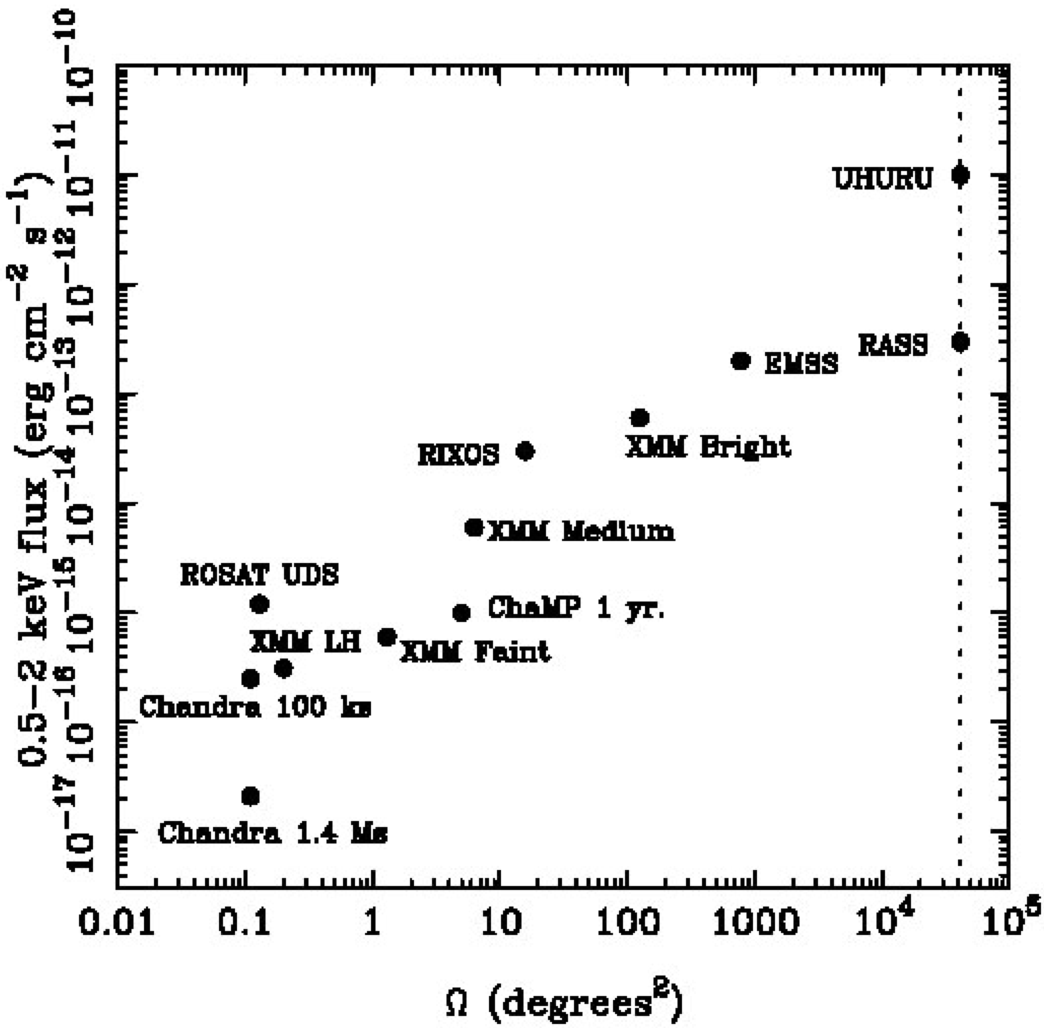
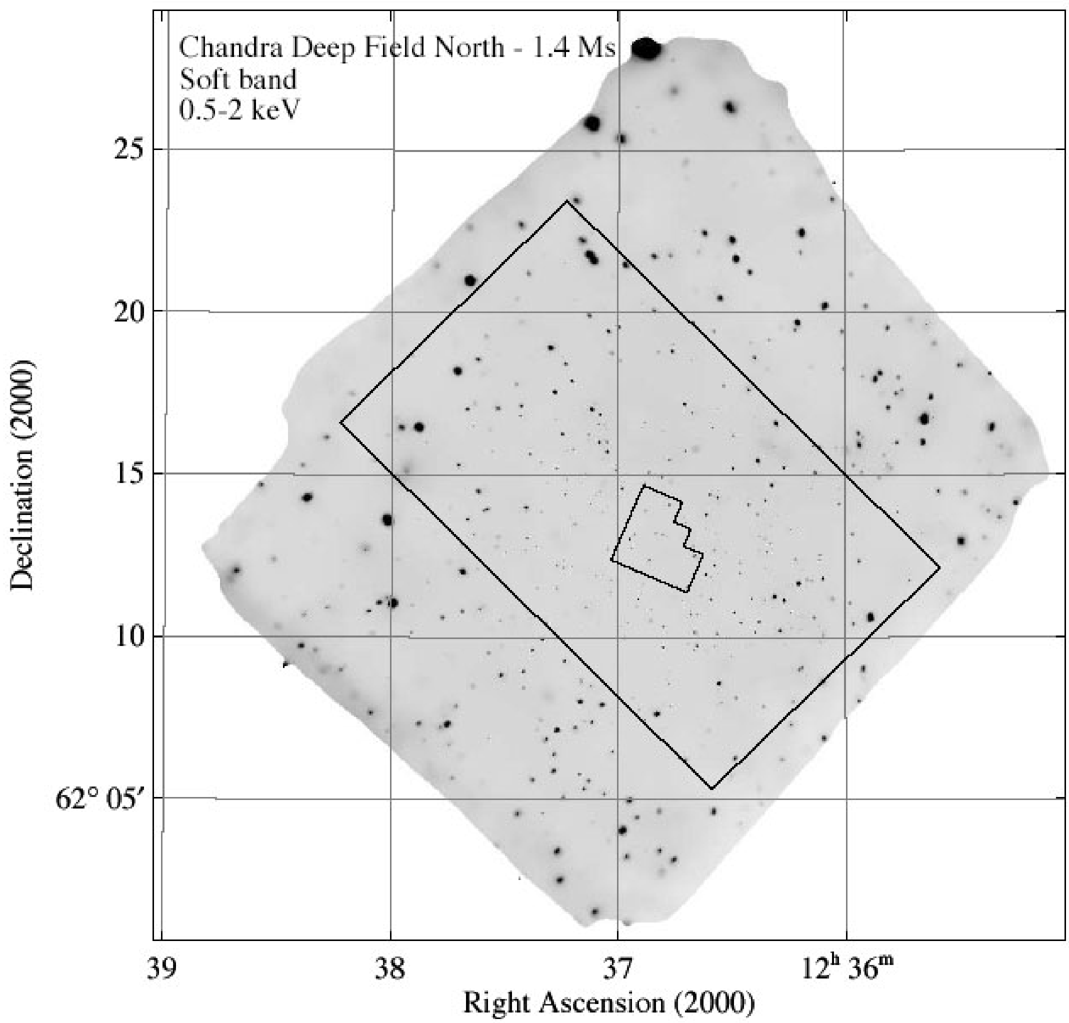
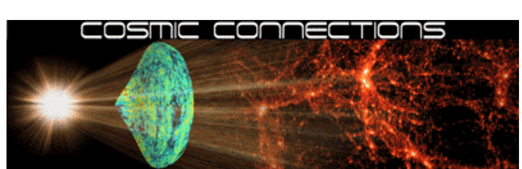


From Brandt, Alexander, Bauer, and Hornschemeier, 2002, Phil. Trans. R. Soc., 360, 2057.

Discrete Source Contributions



From Brandt, Alexander, Bauer, and Hornschemeier, 2002, Phil. Trans. R. Soc., 360, 2057.



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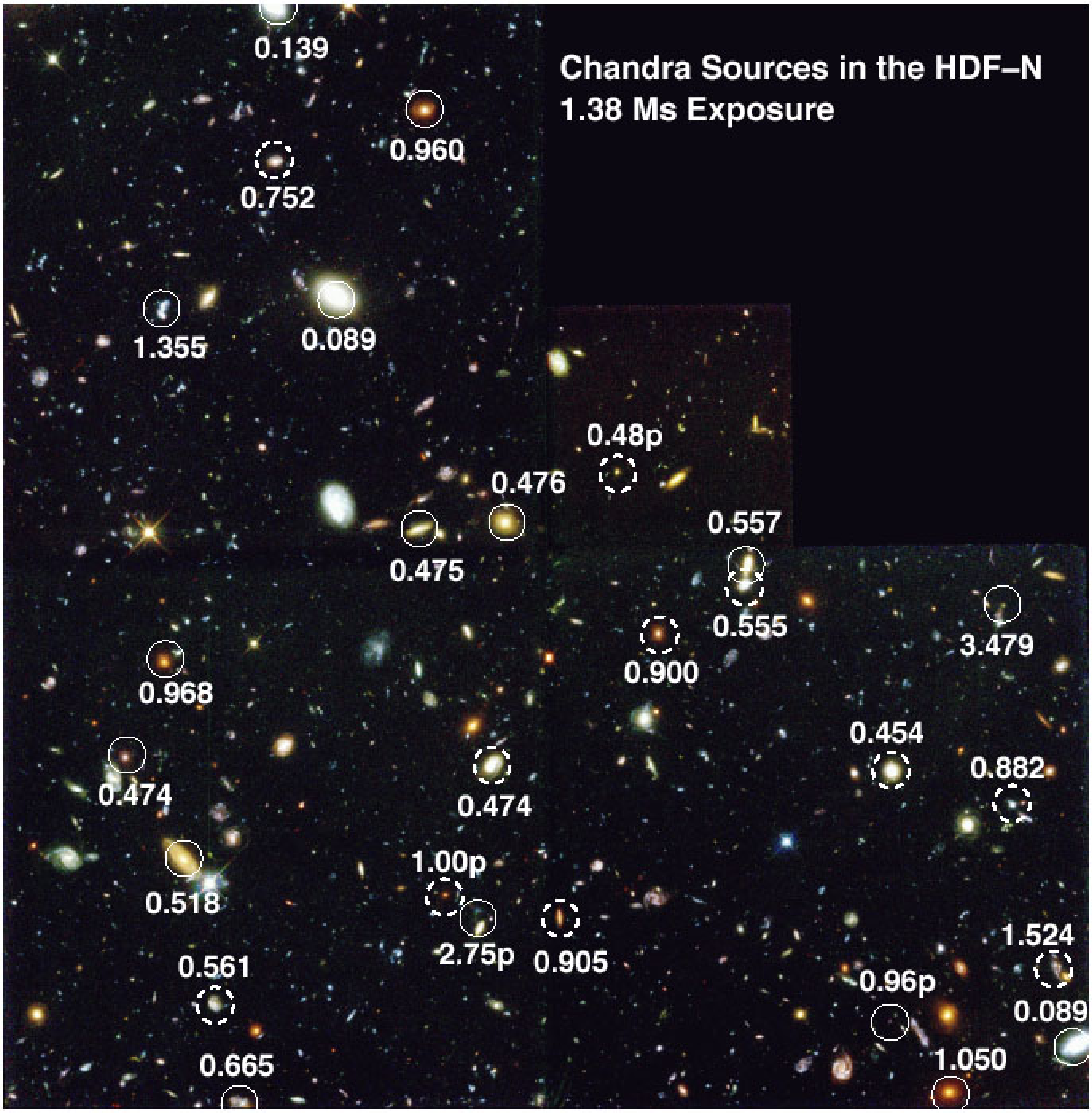

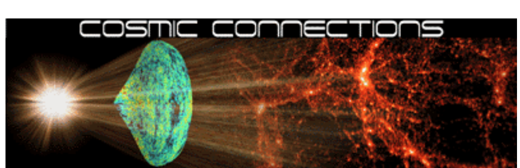

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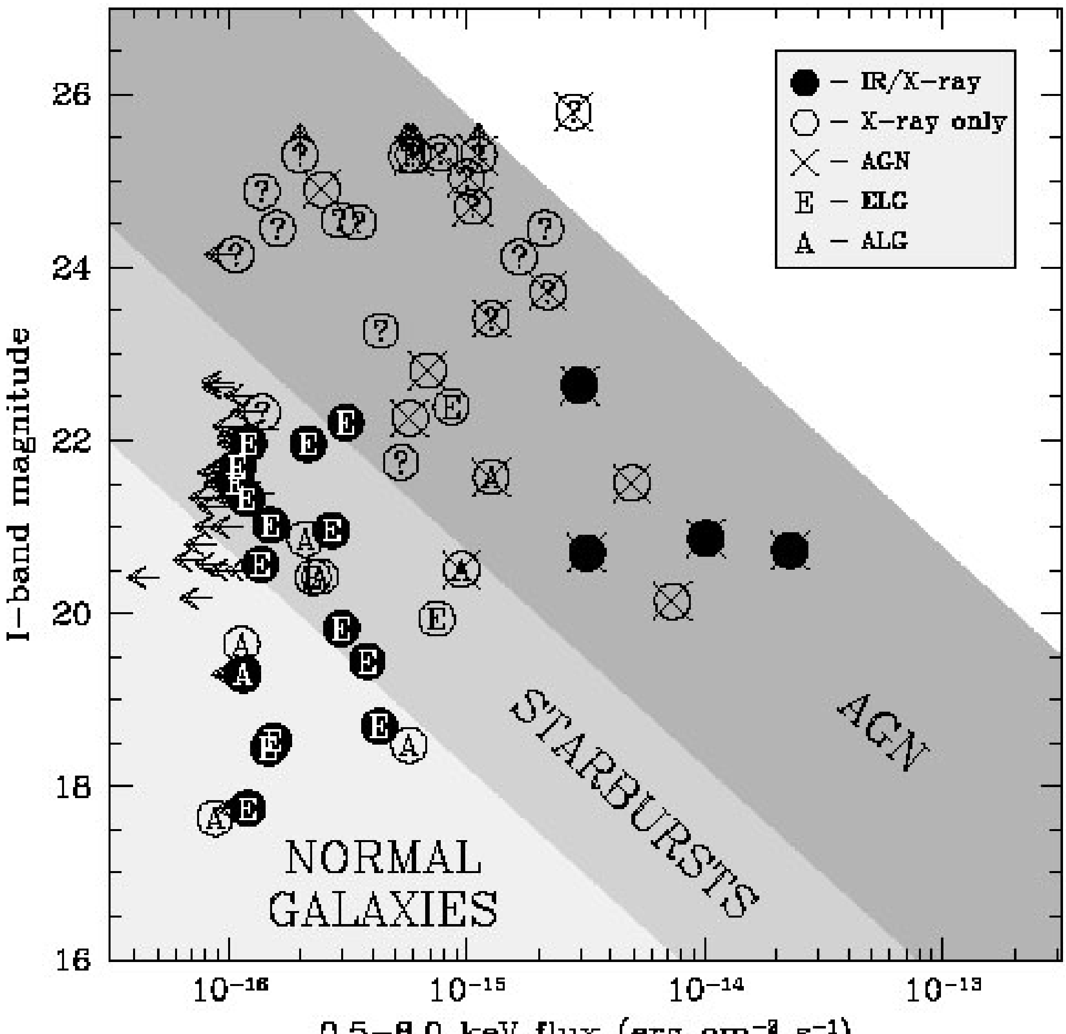
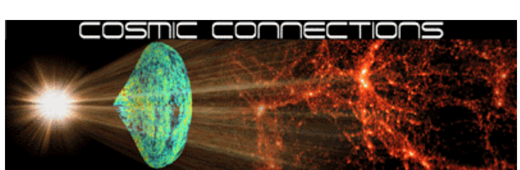
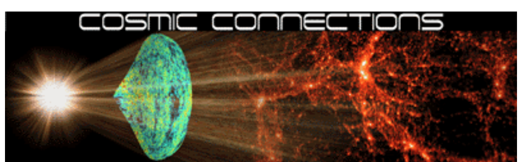




III. Spectral Paradoxes



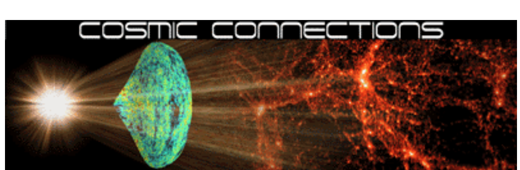
The "Old" Spectral Paradox

* As mentioned earlier, the spectrum of the hard X-ray background (3 - 300 keV) is remarkably well-described by the spectrum of thermal bremsstrahlung radiation with a temperature kT ~ 40 keV. In fact, in a pure χ^2 sense, the thermal bremss fit to the CXB was far superior than the pre-COBE blackbody fits to the CMB!

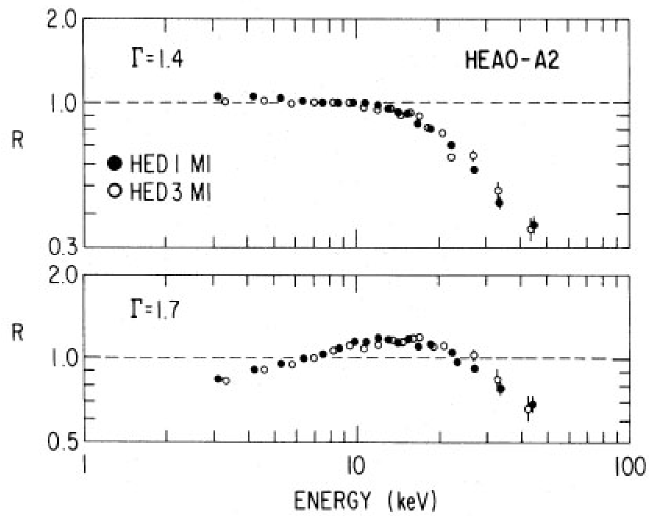
* This gave rise to the supposition (early on), that the CXB might indeed be produced by hot gas in the intergalactic medium (e.g. Field & Perrenod 1977).

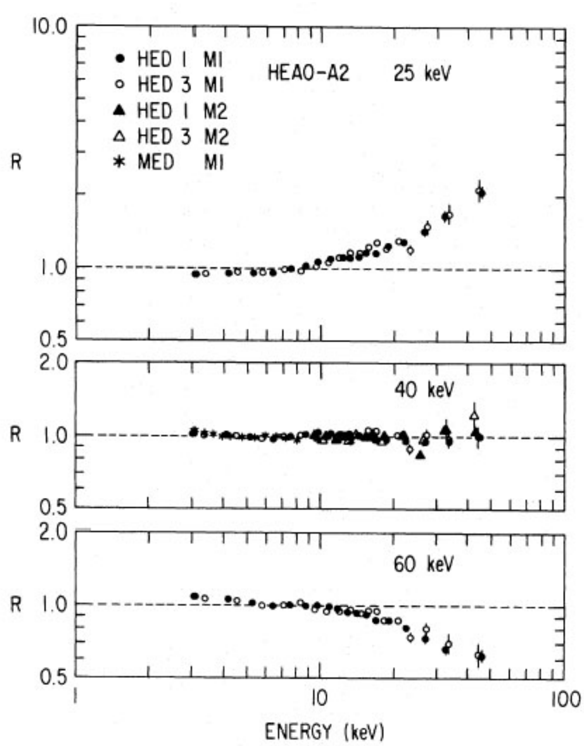
* The cosmological implications of that hypothesis were fairly daunting:
  – The energy density of the CXB emitting gas would be comparable to that of the CMB! This would require a significant reheating of the Universe with the energy output per galaxy ~ 10^{63} ergs (10^{11} SNe).

  – The baryon density of the IGM would also be very high: $\Omega_b \sim 0.46\ \Omega_C$. That conflicts with cosmic nucleosynthesis limits, which are lower by a factor 10.

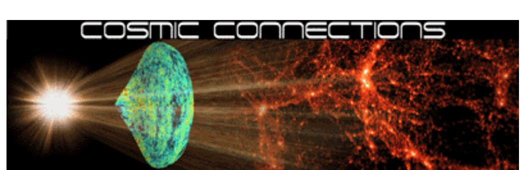


The "Old" Spectral Paradox





From Marshall et al. 1980, Ap.J., 215, 717.



The “Old” Spectral Paradox

* The thermal hypothesis encountered a number of other, much more serious problems, however:

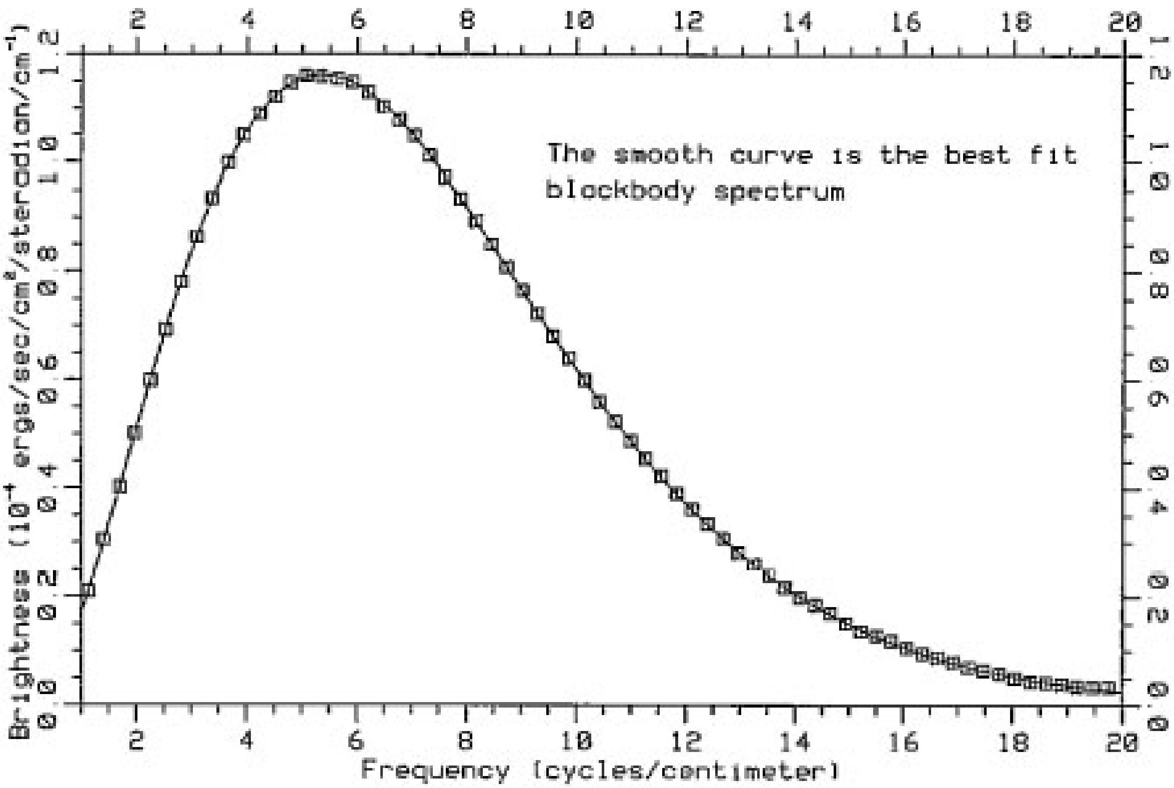
  – Even in the non-imaging era, it was known that at least some of the CXB must be produced by AGN. Subtracting the known, non-evolving source population, yielded a spectrum that no longer fit the spectrum of hot gas.

  – If the heating were due to “galactic explosions”, one would expect the gas to be metal enriched. The lack of any detectable Fe K line or “shoulder” (near 6.7 keV) in the CXB spectrum argued against that picture.

  – But the real nail in the coffin came from COBE: The CMB spectrum shows no distortion from the pure blackbody at the highest frequencies. One would expect to see such a feature due to inverse Compton scattering of CMB photons by the hot electrons in the putative IGM. The upper limit from COBE put the fraction of the CXB due to hot gas at < 0.01%.

* Evidently the good fit to the thermal bremss spectrum was just a “cosmic conspiracy”!

The "Old" Spectral Paradox



From Mather et al. 1990, Ap. J., 354, L37.

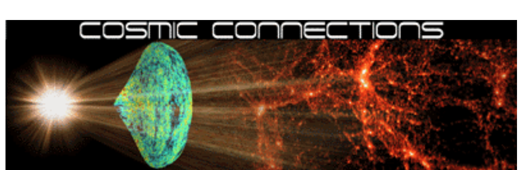
The “New” Spectral Paradox

* Once it became clear that the CXB is largely due to distant point sources, we still needed to verify that the responsible source populations have the right spectral characteristics to synthesize the integrated background spectrum.

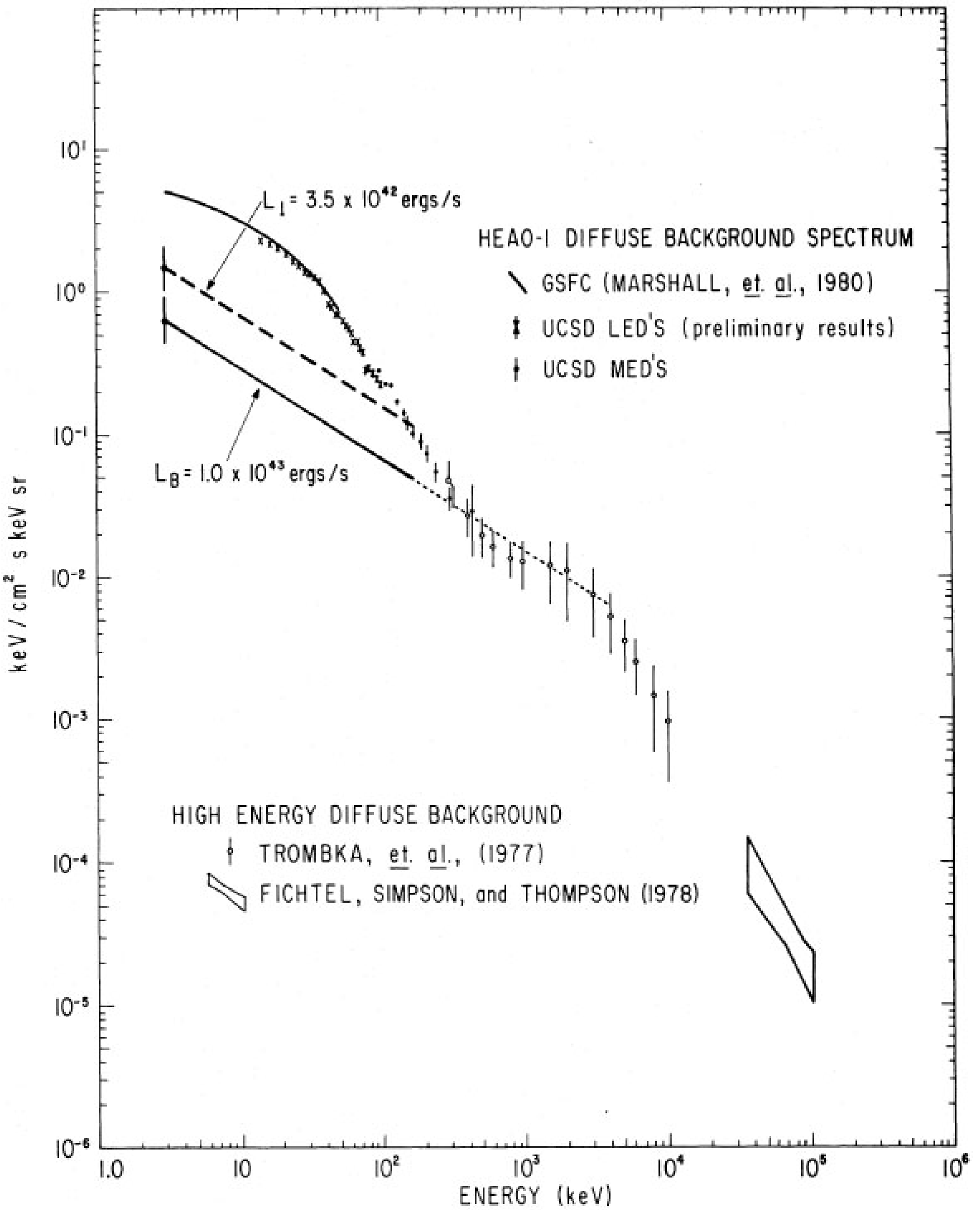
* This presented a severe problem early on. Due to their strongly positive evolution, it seemed likely that AGNs made up the bulk of the background. But the typical measured hard X-ray spectra of bright AGNs had a power law index $\alpha \sim -1.7$.

* In contrast, the mean spectral index of the CXB is ~ -1.4, significantly flatter.

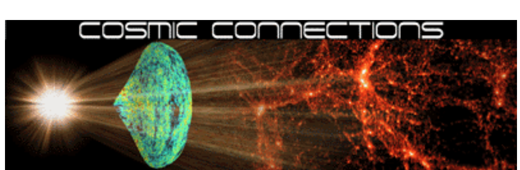
* In addition, the brightest AGNs exhibited no discernible spectral breaks out to several hundred keV. How then do we get the peak at 30 keV?



The “New” Spectral Paradox.



From Rothschild et al. 1983, Ap. J., 269, 423.



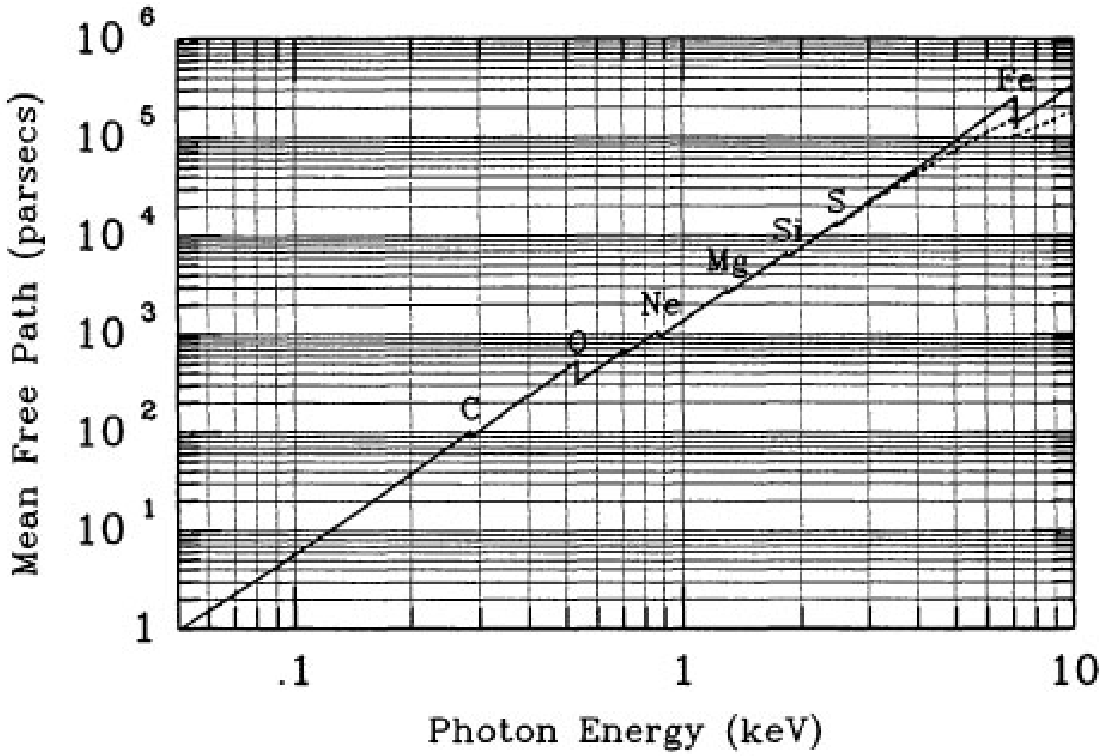
The “New” Spectral Paradox

* To resolve this problem, we must conclude that the spectra of faint AGNs are systematically harder than the spectra of the bright AGNs first measured with the non-imaging experiments.

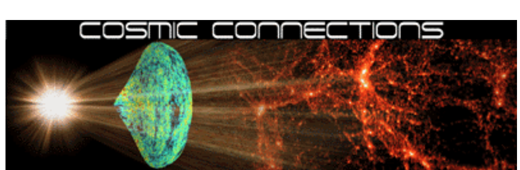
* As first suggested by Setti and Woltjer (1989), one way to achieve this is to invoke a distribution of absorbing column density.

* The cross-section for photoelectric absorption is strongly energy dependent: $\sigma \sim E^{-3}$. Highly absorbed sources are severely deficient in flux at lower energies. With an appropriate distribution in the absorbing column density, N_H, one can indeed achieve a reasonable fit to the integrated CXB spectrum.

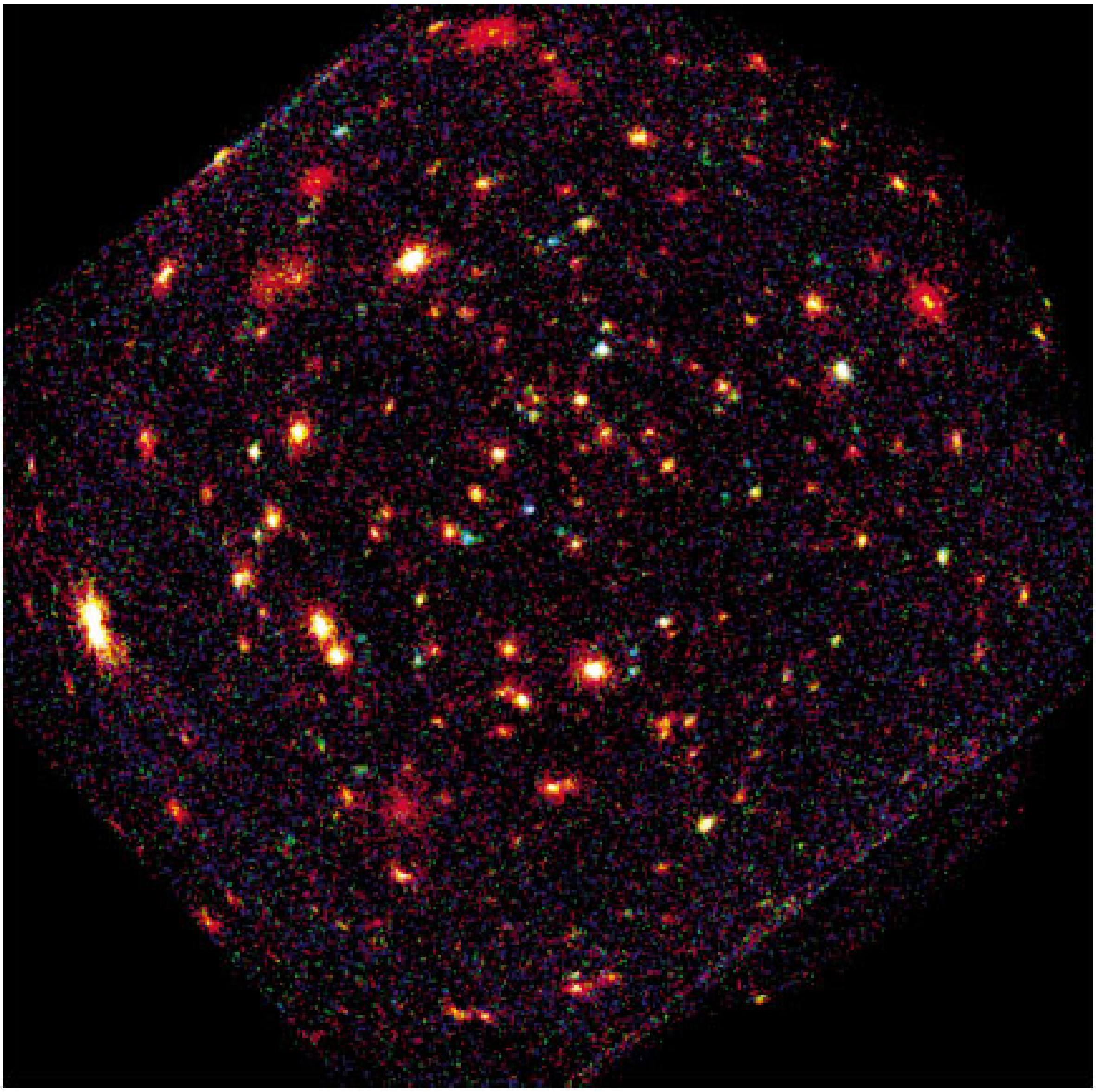
The "New" Spectral Paradox



From McCammon & Sanders, 1990, ARAA, 28, 657.



The "New" Spectral Paradox



From Hasinger et al. 2001, A&A, 365, L45.

The "New" Spectral Paradox

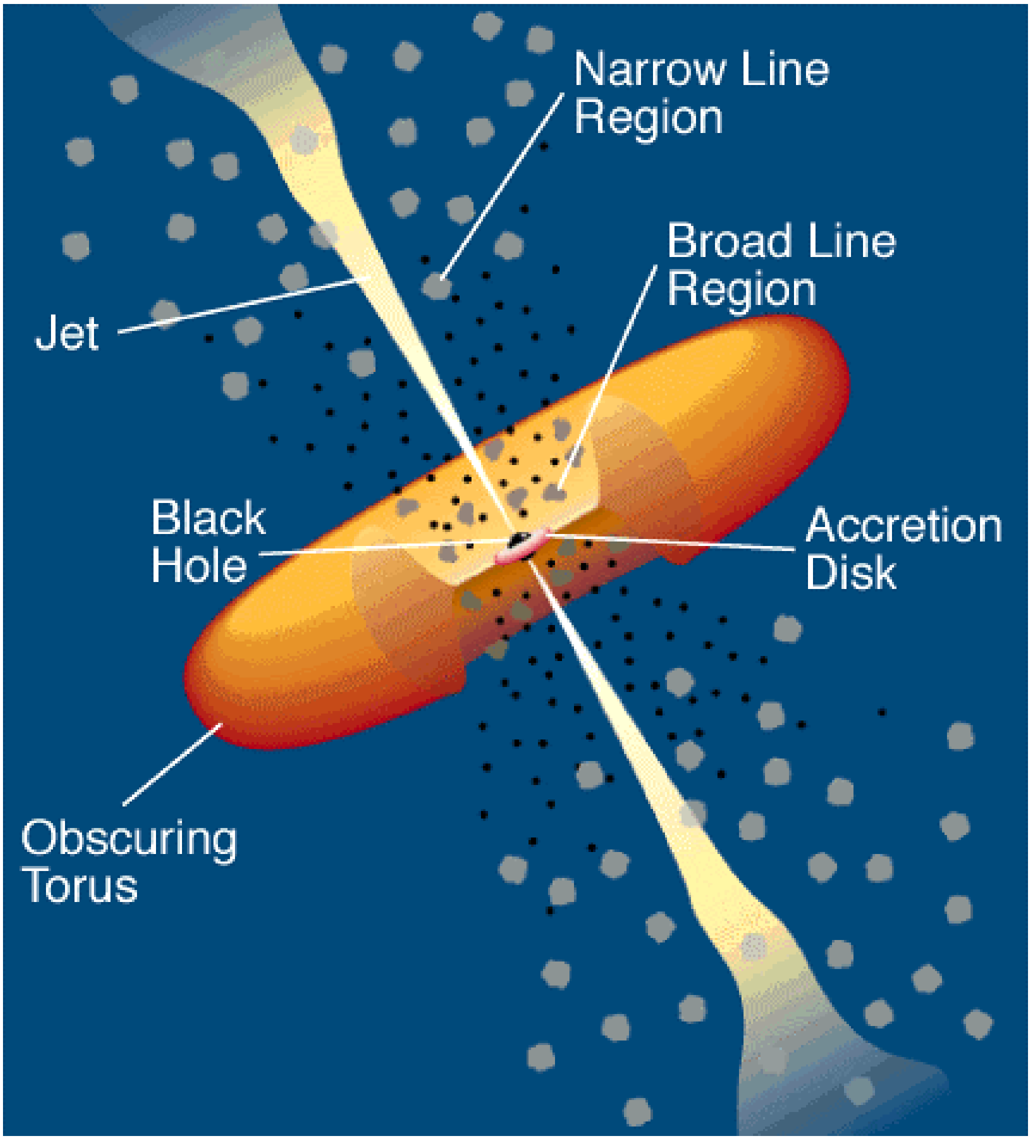
* The absorption idea fits in rather well with so-called Grand Unified Models of AGNs. In these models, the different observational characteristics of various kinds of sources are explained by orientation effects associated with a single basic geometry.

* The accreting black hole is thought to be surrounded by a torus of thick dusty material, presumably rotationally supported due to the inefficient dissipation of angular momentum as material collects toward the center.

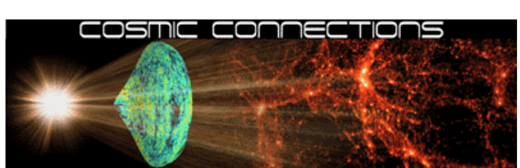
* If viewed at high inclination angles, the central source of X-radiation is highly obscured. If viewed at low inclination, one gets an unobstructed view of the nucleus.

* The covering fraction of the torus is large, so most AGNs are expected to be highly absorbed. This would account for the higher normalization of the Log N - Log S relationship observed for AGNs in the hard X-ray band, versus that found at softer X-ray energies.

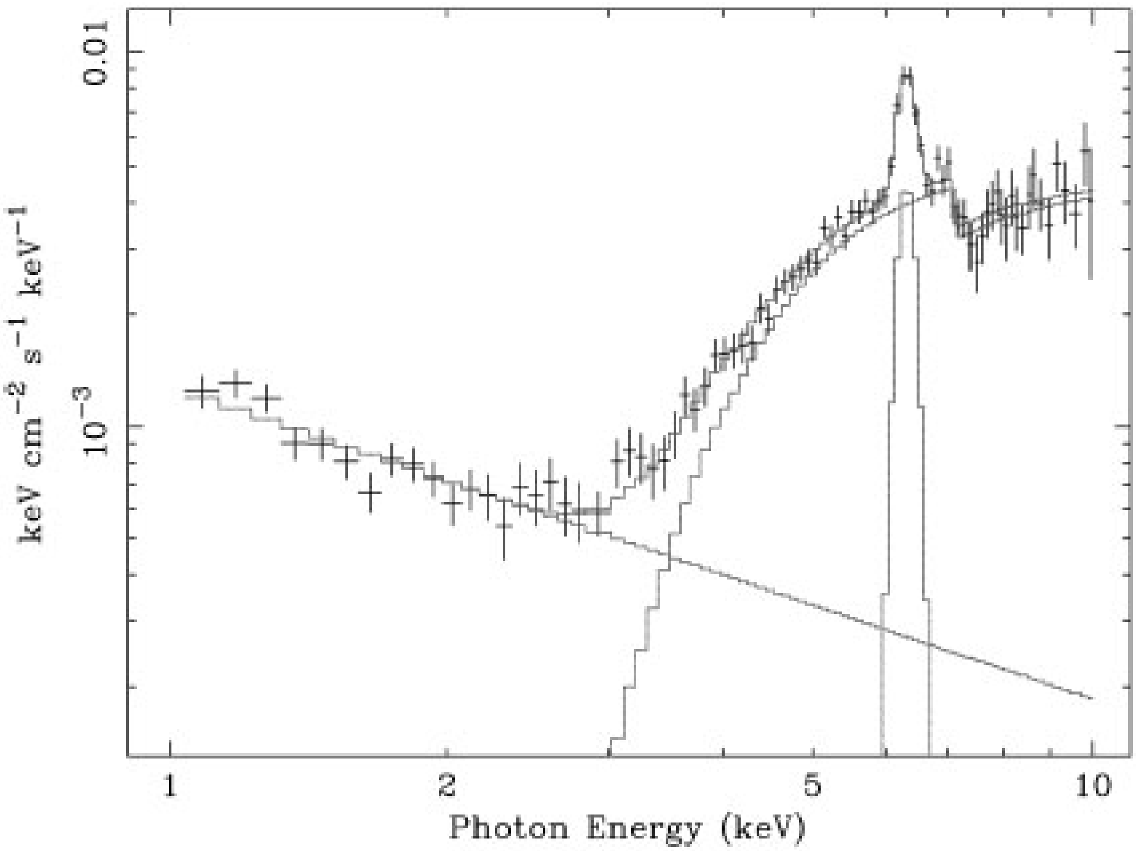
The "New" Spectral Paradox



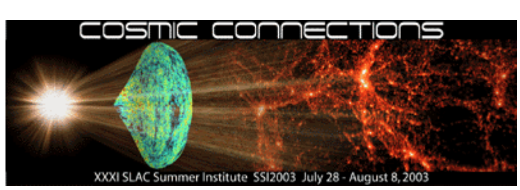
From Urry and Padovani, 1995, PASP, 107, 803.



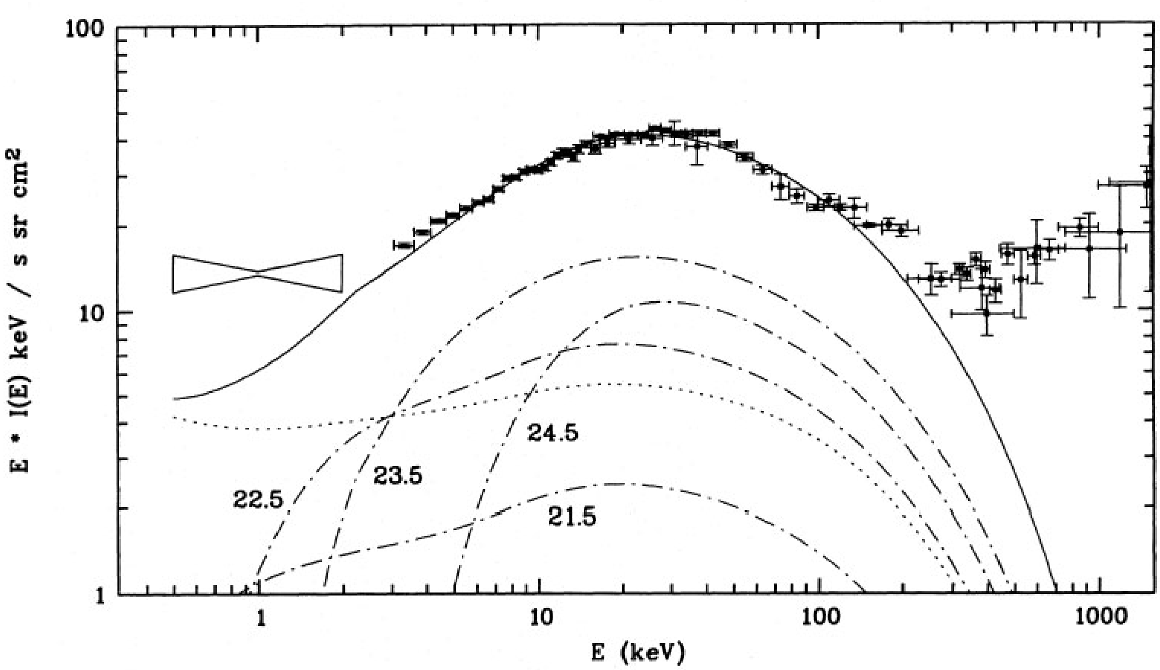
The “New” Spectral Paradox



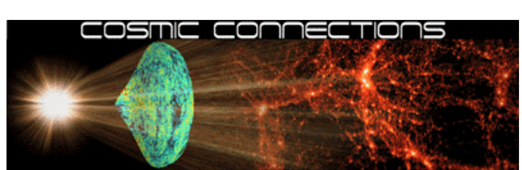
From Moran et al., 2001, Ap. J., 556, L75.



The “New” Spectral Paradox



From Comastri et al. 1995, A&A, 296, 1.



The "New" Spectral Paradox

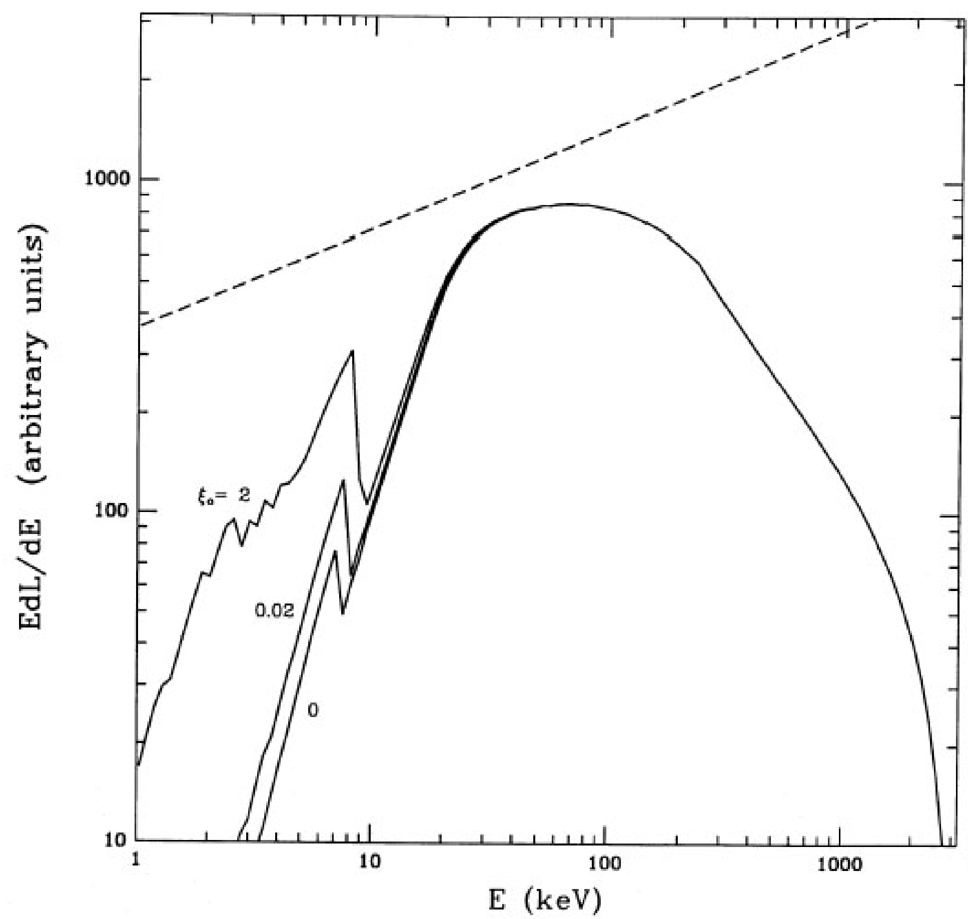
- * Why is there a break in the CXB spectrum at ~ 30 keV? Such an obvious feature should have a simple explanation.

- * Trying to relate it to the electron rest mass (e+e- annihilation?) requires too high a redshift.

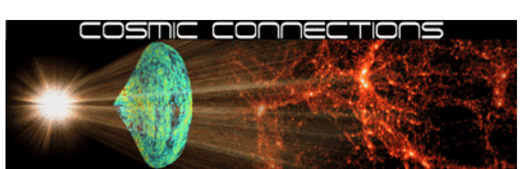
- * But there is another basic effect associated with the electron - Compton reflection. Reflection off cold material creates a broad bump in the spectrum peaking at ~ 100 keV. At much lower energies, photoelectric absorption dominates scattering. At much higher energies, the Compton wavelength shift "moves" photons down to lower energies.

- * Compton reflection is believed to occur naturally in the Grand Unified Model, due to the high covering factor of the dusty torus. The presence of a neutral Fe K fluorescence line adds strong support to this picture.

The "New" Spectral Paradox



From Lightman & White, 1988, Ap. J., 335, 57.



The “New” Spectral Paradox

* Is the “new” spectral paradox resolved? Not quite, there are still some problems.

* More recent work suggests that trying to match both the redshift distribution of the Chandra faint sources and the overall CXB spectrum requires an evolving ratio of Type 2 to Type 1 sources. We need more Type 2’s in the past.

* This flies in the space of the spirit of the grand unified picture. If it is all an inclination effect, why should the ratio evolve with time. Either give up the GUT or give up the successful synthesis of the background.

* In addition, there is a dearth of Type 2 QSO’s - intrinsically bright AGNs which are still heavily absorbed. So there are still mysteries with the CXB!