INTERACTIONS OF NON-THERMAL X-RAYS AND ULTRAVIOLET RADIATION WITH THE INTERGALACTIC GAS

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1. Introduction

We wish to discuss two ways in which non-thermal background X-rays and ultraviolet radiation may interact with intergalactic matter: (i) low energy photons may be intense enough to photoionize the intergalactic medium and maintain it as an H II region; (ii) the recoil associated with Compton scattering of hard X-rays provides an additional heat input into the medium, as well as causing a characteristic modification of the background radiation spectrum. We shall merely summarize our results here, as fuller details are appearing elsewhere (Rees and Setti, 1969).

2. Ionization of Intergalactic Gas by Soft Photons

Observations of quasars with redshifts $z \simeq 2$ indicate that the density of intergalactic neutral hydrogen at the corresponding epoch must have been exceedingly low. For the optical depth shortward of the redshifted Lyman α wavelength to be $\lesssim \frac{1}{4}$, as is observed,

$$n_{\mathrm{H}} \lesssim 3 \times 10^{-11}\,\mathrm{cm}^{-3} \tag{1}$$

(Gunn and Peterson, 1965). This means that if there is a substantial amount of intergalactic gas it must be almost completely ionized. For it to be *collisionally* ionized to the required extent, gas temperatures $\gtrsim 10^6$ K are needed, for present total gas densities $\bar{n} \gtrsim 10^{-6}\,\mathrm{cm}^{-3}$. There is then the problem of avoiding thermal bremsstrahlung emission in excess of the observed soft X-ray background.

If there were an adequate flux of intergalactic ultraviolet radiation, this ionization could be maintained without the necessity for a high gas temperature. No thermal X-rays would then arise from the gas, and an interesting new range of thermal histories for intergalactic matter would be compatible with all the data. The extension of the non-thermal X-ray background towards longer wavelengths may constitute such a flux.

Galactic absorption precludes reliable observations of the X-ray background at energies much below 1 keV. However there seems no reason why the background intensity incident on the Galaxy should not continue to rise towards longer wavelengths,

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unless *intergalactic* absorption is important. If the non-thermal background above ~ 1 keV arises from inverse Compton scattering of black body photons by relativistic electrons with $\gamma > 10^3$, the intensity would definitely be expected to rise at least as steeply as $\propto \nu^{-1/2}$, because this is the spectrum which results when the high energy electrons are degraded. If additional electrons are injected with $\gamma < 10^3$, the radiation spectrum would of course be steeper than this. In order to abbreviate our discussion and to emphasize the main points, we take a simple 'standard' spectrum

$$F(\nu) \propto \nu^{-1} \tag{2}$$

right down to 10 eV, the intensity being normalized to give 20 photons (cm^2 sec ster keV)$^{-1}$ at 1 keV. This spectrum lies within 50% of all the observations above 1 keV. The flux at the Lyman limit would then be

$$F_{\mathrm{Ly}} = 10^{-23} \text{ erg } (\text{cm}^2 \text{ sec } (\text{c/sec}) \text{ ster})^{-1}. \tag{3}$$

Although we have extrapolated by a factor ~ 100 in wavelength beyond the band where reliable data exist, this corresponds to a factor only ~ 10 in electron energy (i.e. down to $\gamma \simeq 100$). The actual intensity at the Lyman limit is obviously very uncertain. However (3) is unlikely to exceed the emitted inverse Compton flux at this energy by as much as an order of magnitude. It may, however, be a more serious *under*estimate, especially if additional components make large contributions to the background radiation below 1 keV. (3) greatly exceeds the predicted ultraviolet flux from galaxies, and is higher than even optimistic estimates of the contribution from quasars, based on extrapolation of their optical spectra (Noerdlinger, 1969).

If this radiation all originated at a redshift z^* (which we shall assume to exceed 2), then the value of F_{Ly} at a redshift $z < z^*$ is $\propto (1+z)^4$. We find that, at $z \simeq 2$, this intensity would be capable of maintaining a level of ionization satisfying (1) if the electron density were as high as $\sim 3 \times 10^{-5}$ cm^{-3} (for an electron temperature ~ 20000 K). This corresponds to a present gas density $\bar{n} \simeq 10^{-6}$ cm^{-3}.

According to the usual 'big bang' cosmologies, the gas would have been cool and neutral (cooler even than the primeval radiation) until objects condensed and released the energy to reheat it. We now consider whether non-thermal radiation could have accomplished this hearing. For a gas density $\bar{n} \simeq 10^{-6}$ cm^{-3}, our 'standard' spectrum yields $20(1+z)$ eV per particle in the form of photons with energy 10–100 eV. The heating must have occurred at $z > 2$, and so sufficient energy would have been available to ionize all the H and He atoms, and to raise the temperature to any value up to $\sim 10^5$ K (we return to the question of the temperature later). The details of the heating would be complex. However, the results are unlikely to differ much from the idealised situation in which the photons are generated suddenly and uniformly at some redshift z^*. The heating would occur without much distortion of the spectrum (2), and the temperature immediately after the ionization (which is simply related to the mean energy of the absorbed photons) would be ~ 25000 K. (An important feature of this type of heating is that it naturally 'switches off' once the medium has been ionized. One of the difficulties with other processes – e.g. cosmic ray heating – is that the heat input has to be very nicely adjusted in order to avoid the temperature shooting up to $\sim 10^8$ K, in which case there would be too much thermal X-ray emission even if $\bar{n} \simeq 10^{-6}$ cm^{-3}, once the gas breaks through the 'thermal barrier' at 10^4–10^5 K.)

In the subsequent expansion, the heat input via photoionizations partially compensates for the radiative and adiabatic losses. The temperature at $z \simeq 2$ would depend on when the heating occurred, but, for $\bar{n} \simeq 10^{-6}$ cm^{-3}, would be 10000–20000 K. Assuming free expansion down to the present epoch, the temperature could now be as low as ~ 4000 K, even if the ionization were still maintained. It is interesting to see whether the medium could have recombined by the present time (this is not possible when the ionization at $z \simeq 2$ is collisional). The optical depth at the Lyman limit would be ~ 3 times greater than at $z \simeq 2$. However it must then have been $\lesssim \frac{1}{4}$ (corresponding to an optical depth $\lesssim \frac{1}{4}$ in Lyman α), so that recombination seems rather unlikely. The number of recombinations during the expansion time-scale decreases only slightly more slowly during the expansion than the flux of ionizing photons (even when one allows for the falling temperature).

This situation would change if the gas did not expand freely, so that its local density was not proportional to $(1+z)^3$. For example, it is possible that the intergalactic gas is now all concentrated in clusters of galaxies. Since clusters occupy a few per cent of the volume of space, they could not have separated out before $z \simeq 2$. We may approximate the situation by supposing that up to $z \simeq 2$ they expand freely, but afterwards the density of the gas stays constant. The photoionization rate would still be $\propto (1+z)^4$, whereas the recombination rate would in fact *increase*, because radiative cooling decreases the temperature. The gas within clusters could therefore have become predominantly neutral. (In the case of collisional ionization, the concentration of the gas into clusters greatly aggravates the situation regarding the bremsstrahlung X-rays; the temperature remains high because of the absence of adiabatic cooling, and the higher density promotes more efficient X-ray emission.)

If the gas had now recombined, no ultraviolet background radiation beyond the Lyman limit would survive – indeed, there may be significant absorption right up to 1 keV. Sunyaev (1969) has argued that the existence of low density H I bridges between galaxies, and in an extended region around M31, is inconsistent with the presence of an intense background in the far ultraviolet. The flux (3) is actually consistent with Sunyaev's limit, although a gas with $\bar{n}$ much greater than $\sim 10^{-6}$ cm^{-3} could not have been maintained ionized at $z \simeq 2$ without F_{Ly} violating this limit (unless the gas has now recombined). However it appears to us that Sunyaev's argument can be evaded. The incident radiation is only capable of maintaining a layer of gas of density n_e and thickness L cm ionized if

$$L \lesssim (10^{23} F_{\mathrm{Ly}}) \cdot 2 \times 10^{14}\, T^{1/2} n_e^{-2}. \tag{4}$$

The observed H I discussed by Sunyaev may be surrounded by ionized regions of enhanced density whose parameters correspond to approximate equality between the two sides of (4). A stationary situation would be possible if, for example, the Local Group contained ionized hydrogen of density $\sim 10^{-3}$ cm^{-3}.

3. Scattering of Hard X-Rays

Hard X-rays have an insignificant chance of being absorbed photoelectrically, but they also may affect the intergalactic gas, at least if they come from very large redshifts.

When a photon of frequency ν is scattered, it transfers a fraction $\sim h\nu/mc^2$ of its energy to the electron. Consequently electron scattering has no effect on the spectrum or intensity of background radiation at optical or radio wavelengths, though it obviously obscures discrete sources. However a photon with $h\nu \simeq mc^2$ which is scattered just once gives up $\sim \frac{1}{2}$ its energy to the electron. Thus, if radiation with spectrum (2) were emitted at a redshift $z_{\tau=1}$ such that the universe had optical depth ~ 1 to Thomson scattering, we would observe an attenuation of $\sim 50\%$ below the power law at energies $\sim mc^2(1+z_{\tau=1})^{-1}$. The energy lost by the photons would have gone into the gas, but would not be capable of ionizing it completely. Note that this process is not affected by whether the gas is ionized or neutral, since the energy transferred by the relevant photons in the recoil is enormously higher than the binding energy of hydrogen or helium.

4. Conclusions

A plausible extrapolation of the non-thermal X-ray background into the ultraviolet yields a flux of photons around the Lyman limit which exceeds the likely flux arising from other processes. The background radiation probably originated at $z \gtrsim 2$, and could ionize an intergalactic gas of present density $\sim 10^{-6}$ cm^{-3}. If the gas were smoothly distributed through the universe, it would probably still be ionized, but if it were now concentrated in clusters it could have recombined. The electron temperature can be calculated in terms of the spectrum of the ionizing photons, and would be $\lesssim 20000$ K. A stronger ultraviolet flux than our assumed extrapolation could ionize a denser gas, and still the temperature would be too low for thermal X-rays to be emitted.

Hard X-rays are degraded when they are scattered by thermal electrons. This modifies their spectrum, and transfers energy to the gas.

References

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