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OBSERVED GALACTIC HARD X-RAY EMISSION AS AN INDICATION FOR COSMIC RAY HEATING OF INTERSTELLAR HI

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Observed Galactic Hard X-Ray Emission As An Indication For Cosmic Ray Heating of Interstellar HI

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ABSTRACT

The intensity and spectral shape of the diffuse X-ray emission by the galactic disk are found to be consistent with bremsstrahlung radiation arising from knock-on collisions of subrelativistic cosmic ray protons with atomic electrons of interstellar HI. This association is based upon relating the observed X-ray emission with (1) recent estimates of the ionization rate for heating the interstellar gas in HI regions, and (2) the lifetime of cosmic rays confined to the galactic disk. The possible role of cosmic ray electrons in the production of this diffuse galactic X-ray emission is examined, and several arguments lead to the conclusion that it is probably unimportant.

I. X-RAY EMISSIVITY

Diffuse X-ray emission by the galactic disk within the band ϵ = (1.4 - 18) keV was discovered in a rocket observation (Cooke, Griffiths and Pounds 1969) and confirmed by an OSO-3 satellite observation (Schwartz 1970; Schwartz, Hudson and Peterson 1970) within the band ϵ = (7.5 - 12.5) keV. The 8 point spectrum measured by Cooke et al. (1969) and the flux measured by Schwartz et al. (1970) may be adequately described by

$$I_\epsilon = 0.15 \text{ keV (keV cm}^2 \text{ sec rad)}^{-1} \qquad (1)$$

for ϵ = (1.4 - 12.5) keV (see Figure 1). However, Schwartz et al. (1970) did not detect this source in their channels covering ϵ = (12.5 - 115) keV and deduce from the corresponding upper limits that the energy spectral index exceeds 2.2 for this band; Bleeker and Deerenberg (1970) obtain similar upper limits from a balloon borne experiment. The intensity (I) of the integral spectrum may therefore be approximated by

$$I \approx \int_{1.4 \text{ keV}}^{12.5 \text{ keV}} I_\epsilon \, d\epsilon = 17 \times 10^2 \text{ eV (cm}^2 \text{ sec rad)}^{-1}. \qquad (2)$$

We pursue the indication by Cooke et al. (1969) that their data show a correlation with hydrogen columnar density. This allows us to calculate the X-ray emissivity (η) for galactic hydrogen, as follows:

$$\eta = 4\,\pi\,(I/N) \left[1 + \ell n\,(2\,\theta_d/\theta_g)\right]^{-1} \text{ eV (sec atom)}^{-1}, \qquad (3)$$

where N is the columnar density (H atoms/cm^2) for the total thickness of the galactic disk, θ_d is the band width of galactic latitudes covered by the angular response (FWHM) of the detector and θ_g is the angular thickness (FWHM) of the hydrogen disk at the galactic longitude viewed by the detector; we consider $\theta_d \geq \theta_g$. In evaluating η we take $\theta_d = 4^o$, $\theta_g = 2^o$ and $N = 73 \times 10^{19}$ atoms cm^{-2} (McGee and Murray 1961). Using the intensity I obtained in equation (2), equation (3) yields

$$\eta = 12 \times 10^{-18} \text{ eV (sec atom)}^{-1}. \tag{4}$$

II. ELECTRON BREMSSTRAHLUNG

The X-ray spectrum shown in Figure 1 is consistent with an essentially flat bremsstrahlung spectrum that breaks within the interval $\epsilon \approx (10 - 20)$ keV. If this radiation is due to subrelativistic cosmic ray electrons, then these particles are constrained to be predominantly within the energy band $E_e \approx (10 - 20)$ keV. The radiation fraction (f) of the electron's total collision loss rate in hydrogen may be obtained from the compilation by Berger and Seltzer (1964), and the values of interest are:

$$f_{10 \text{ keV}} = 38 \times 10^{-6} \tag{5a}$$

$$f_{20 \text{ keV}} = 67 \times 10^{-6} , \tag{5b}$$

The total rate (q) of electron energy dissipation per hydrogen atom corresponding to the X-ray emissivity is therefore given by

$$q = \eta/f \text{ eV (sec atom)}^{-1}. \qquad (6)$$

From equations (4), (5) and (6) we obtain broad limits on q, viz:

$$q = (18 - 32) \times 10^{-14} \text{ eV (sec atom)}^{-1}. \qquad (7)$$

More sensitive and detailed measurements of the galactic disk X-ray emission over the band $\epsilon \approx (1 - 20)$ keV should greatly reduce the uncertainties on η, remove the ambiguity on the effective energy at which to evaluate f, and therefore allow for a more precise determination of q than that represented by the limits given by equation (7). Nevertheless, these limits permit us to make a meaningful comparison with estimates of the interstellar HI ionization rate (ζ) per hydrogen atom arrived at by considerations independent of those already discussed here. Since it takes an average energy loss of 36 eV per atom ionized in hydrogen (Dalgarno and Griffing, 1958), equation (7) may be used to evaluate ζ, as follows:

$$\zeta_1 \equiv q/36 = (5 - 9) \times 10^{-15} \text{ (sec H atom)}^{-1}. \qquad (8)$$

Several recent theoretical descriptions (Pikel'ner, 1967a, 1967b; Balasubrahmanyan, Boldt, Palmeira, and Sandri 1967, 1968; Spitzer and Tomasco 1968; Spitzer and Scott 1969; Goldsmith, Habing, and Field 1969) of ionization and thermal equilibria for interstellar HI regions, based upon current models for the interstellar gas, indicate that $\zeta \approx 10^{-15}$ (sec)$^{-1}$. Hjellming, Gordon and Gordon (1969) find that observed pulsar dispersion measures may be best fitted with such a model for

$$\zeta_2 = (2.5 \pm 0.5) \times 10^{-15} \text{ (sec H atom)}^{-1}. \tag{9}$$

For an equilibrium situation, the rate of electron-ion recombination is the most direct measure of ζ; recent observations of Hβ hydrogen line emission from interstellar HI (Reynolds, Roesler, Scherb and Boldt 1970; Reynolds 1970) measure the recombination rate, and the corresponding ionization rate could be as high as

$$\zeta_3 \approx 10^{-14} \text{ (sec H atom)}^{-1} \tag{10}$$

A comparison of ζ_1 with ζ_2 and ζ_3 makes it clear that the ionization processes responsible for the heating of interstellar HI could very well account for the observed X-ray emission of the galactic disk if indeed these ionization processes were due to subrelativistic cosmic rays. On the other hand, if the ionization is itself due to soft X-rays and/or ultraviolet radiation, then we would expect to see many soft X-ray emitting objects (i.e., $\sim 10^4$ strong sources or $\sim 10^9$ weak sources) within the galactic disk (Werner, Silk and Rees 1970) or we would require a huge energy emission in the ultraviolet ($U \gtrsim 10^{50}$ ergs) from each supernova or hot O star (Bottcher, McCray and Dalgarno, 1970). It should be emphasized, however, that hard X-ray emission is a necessary consequence of ionization by cosmic rays (Boldt and Serlemitsos 1969) and its observation constitutes a vital piece of supporting evidence; the absence of X-ray emission from interstellar HI would prove that the ionization is not caused by suprathermal particles.

If there were a population of subrelativistic cosmic ray electrons within the band $E_e \approx (10 - 20)$ keV sufficient for heating interstellar HI, then these electrons would require a compensating acceleration in the interstellar medium (Pikel'ner and Tsytovich 1969). The collision loss lifetime ($\tau_e \equiv E_e/\dot{E}_e$) for these electrons within the galactic disk is on the order of 10^3 years, which is several orders of magnitude smaller than the confinement lifetime for cosmic rays within the disk. Pikel'ner and Tsytovich (1969) conclude that the interstellar medium could not maintain a suitably high equilibrium level of such electrons.

III. PROTON BREMSSTRAHLUNG

Hayakawa (1960) first proposed that subrelativistic cosmic ray protons might be responsible for the heating of interstellar HI, Balasubrahmanyan et al. (1967, 1968) analyzed the satellite observed spectrum of such protons and suggested looking for associated interstellar bremsstrahlung X-rays and hydrogen recombination line emission, and Boldt and Serlemitsos (1969) exhibited that there would be a detectable X-ray flux from the disk at $\epsilon \leqslant 15$ keV. Applying the kinematic prescription pointed out by Boldt and Serlemitsos (1969), we note that the bremsstrahlung as well as the elastic collision losses for a 10 keV ($\beta = 0.2$) electron in hydrogen equal those for an 18 MeV ($\beta = 0.2$) proton in hydrogen; we recall that electron bremsstrahlung arises from the collision with an atomic nucleus (e.g., proton for hydrogen) while proton bremsstrahlung arises from the collision with an atomic electron. Therefore, as regards the determination of the ionization rate (ζ_1) inferred from the observed galactic X-ray emission, the numerical results of the preceeding analysis

(§ II) for electrons of E_e = (10 - 20) keV in hydrogen apply directly to the corresponding analysis for protons of E_p = (18 - 36) MeV in hydrogen. However, the considerably larger energy associated with such equivalent protons makes the collision loss lifetime correspondingly longer; the collision loss lifetime for protons of E_p = (18 - 36) MeV is

$$\tau_p \equiv E_p/\dot{E}_p = (1 - 3) \times 10^6 \text{ years}, \tag{11}$$

where the average number density of the hydrogen in the galactic disk, needed for computing equation (11), has been taken as 1 cm^{-3}. This lifetime is comparable to recent estimates of a few million years for the mean lifetime of cosmic rays with respect to escape from the galactic disk (Shapiro and Silberberg 1970; Ramaty, Reames, and Lingenfelter 1970). Therefore, interstellar acceleration is not required for the protons and, furthermore, we expect the equilibrium spectrum of such protons in the interstellar medium to change slope towards cut-off within this energy band, even though the source spectra of these particles could well extend smoothly to lower energies.

For a power law proton source spectrum, we expect that the interstellar equilibrium spectrum will exhibit a change in spectral index of 2 between the high energy regime where escape from the galactic disk dominates the lifetime and the low energy regime where collision losses dominate the lifetime. This situation provides us with a natural explanation for an X-ray bremsstrahlung spectrum that exhibits an apparent break within ϵ = (10 - 20) keV, with a change in spectral index of 2 over this band. The required proton energy is comparable to that advocated by Pikel'ner (1967a, 1967b), who concluded that $\langle E_p \rangle \approx 25$ MeV for an energy density of 1 eV/cm^3 for these particles, and by Balasubrahmanyan et al. (1967, 1968) who described a model spectrum with an effective $E_p \gtrsim 15$ MeV. It is substantially higher energy than the 2 MeV/nucleon sub cosmic rays postulated by Spitzer and Tomasko (1968) to account for the heating of interstellar HI; Brown (1970) discusses the soft (ϵ < 1 keV) X-ray bremsstrahlung emission from the interstellar gas that would be associated with such a flux, and Silk and Steigman (1969) discuss the X-ray line emission to be expected from the electron recombination of the heavy nuclei associated with this sub cosmic ray population.

The spallation products (e.g., Li, Be, B) of nuclear reactions between subrelativistic cosmic ray nuclei and the interstellar gas provide a measure of their flux (Reeves, Fowler, and Hoyle 1970; Fowler, Reeves and Silk 1970). The observed abundances in stars, presumed to be constructed from gas that has always resided in the galactic cosmic ray environment, indicate that the cosmic ray flux above 5 MeV/nucleon is not sufficient to provide an ionization rate $\zeta \approx 10^{-15}$ sec^{-1}. As pointed out to the author by Reeves (1970), the resolution of this problem might involve replenishing the cosmic ray contaminated gas of the disk with relatively virgin gas from outside the dominant cosmic ray environment and/or stellar reprocessing of the interstellar gas in several cycles.

IV. RELATIVISTIC ELECTRON RADIATION

Maraschi, Perola and Schwarz (1968) noted the possible role of relativistic cosmic ray electrons in producing X-rays via inverse Compton scattering of starlight. The flux of electrons required to account for the observed galactic X-ray emission would ionize the interstellar gas (Cooke et al. 1969; Rees and Silk 1969) at the rate $\zeta = 3 \times 10^{-16}$ (sec)$^{-1}$, which is an order of magnitude smaller than ζ_1, ζ_2 or ζ_3 (equations (8), (9) and (10)) of the preceeding discussion. The electron energies effective for the inverse Compton production of X-rays in the band $\epsilon = (1 - 10)$ keV from starlight would be $E_e = (13 - 41)$ MeV. The collision loss lifetime for a 41 MeV electron in the galactic disk is

$$\tau_e = 5 \times 10^6 \text{ years.} \qquad (12)$$

If the confinement lifetime for cosmic ray electrons is the same as given by equation (12), then the observed inverse Compton X-ray spectrum would flatten below $\epsilon = 10$ keV, with a spectral index change of 1/2. However, the spectral index for the observed X-ray emission by the galactic disk clearly changes by more than 1/2 over the interval $\epsilon = (10 - 20)$ keV, (see Figure 1); a spectral index change of ~ 2 appears to be consistent with the data. Furthermore, if the electron spectrum used by Rees and Silk (1969) over the band $E_e = (10 - 100)$ MeV is extrapolated to $E_e = 270$ MeV, then the intensity obtained is about an order of magnitude higher than that for the electrons responsible for the galactic synchrotron radio emission observed at $\nu \approx 1$ MHz (Alexander, Brown, Clark, and Stone 1970; Goldstein, Ramaty and Fisk 1970).

The inverse Compton scattering of GeV energy cosmic ray electrons on the far infra-red background in the millimeter range (0.4 - 1.3 mm) has been proposed (Shen 1969; Cowsik and Yash Pal 1969) as a possible explanation of the observed diffuse galactic X-ray emission at $\epsilon \leqslant 10$ keV. However, Bleeker and Deerenberg (1970) and Schwartz et al. (1970) have shown that the upper limits for the galactic X-ray flux at higher energies (see Figure 1) are inconsistent with such a model.

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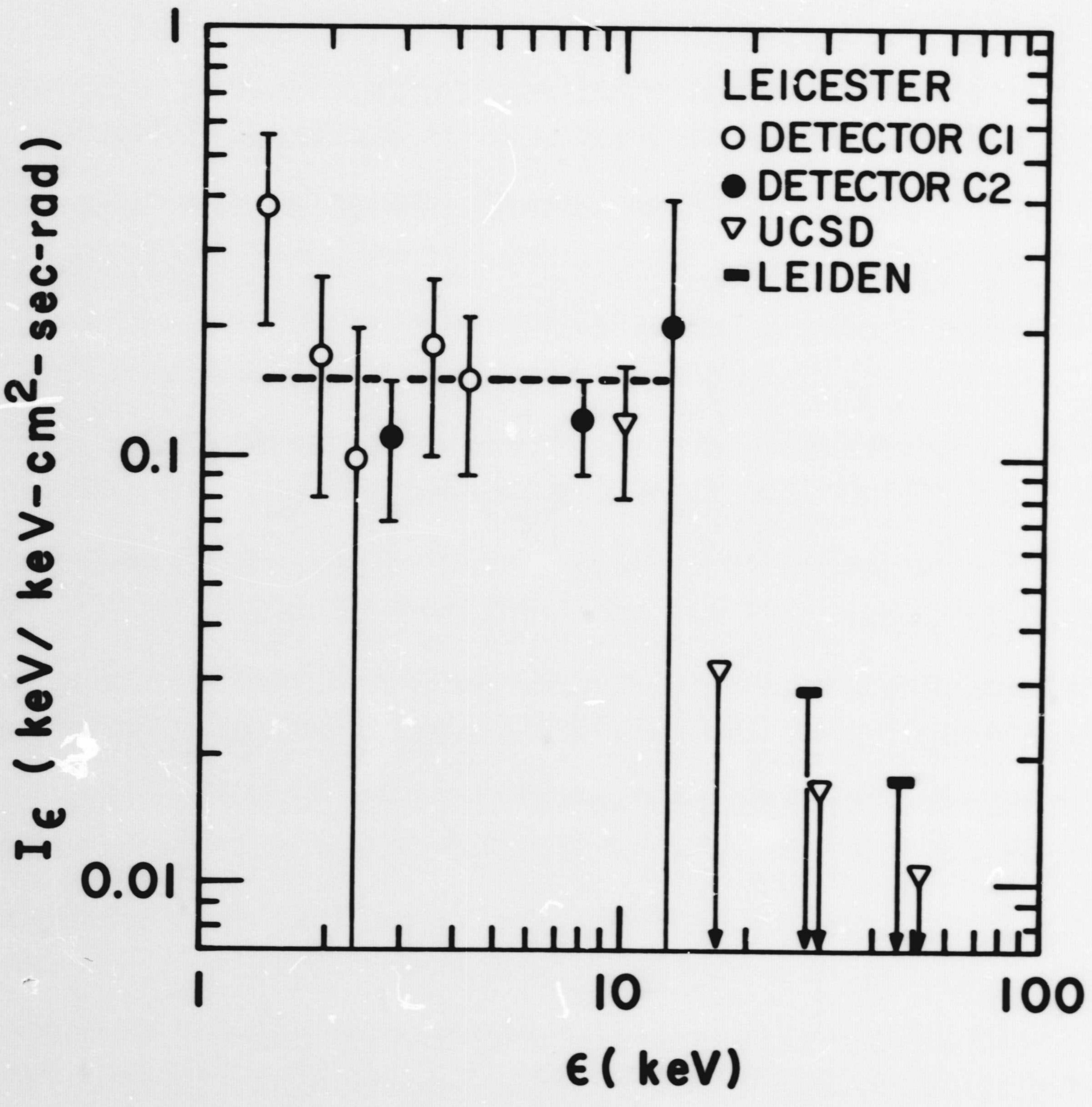
Figure 1

Spectral intensity (I_ϵ) vs ϵ, for the X-ray emission from the galactic plane as observed in the region $\ell^{II} \approx (250 \pm 40)^o$ by the University of Leicester (Cooke, Griffiths and Pounds 1969), and in the regions $\ell^{II} \approx 150^o$ and $\ell^{II} \approx 240^o$ by the University of California at San Diego - UCSD (Schwartz, Hudson and Peterson 1970; Schwartz 1970). The upper limits given by the group at Leiden (Bleeker and Deerenberg 1970) were obtained at $\ell^{II} \approx 150^o$. The horizontal dashed line indicates the spectral intensity of equation (1).


LEICESTER
DETECTOR C1
DETECTOR C2
UCSD
LEIDEN
I_ϵ (keV/ keV-cm^2- sec-rad)
1
0.1
0.01
1
10
100
ϵ (keV)