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Cosmic X Rays and γ Rays*

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The observed diffuse x- and γ-ray spectrum is analyzed, and consequences are deduced for Compton-scattering models in intergalactic space. The putative far-infrared radiation is examined for its effects on (1) interpretation of the diffuse x- and γ-ray observations, (2) Compton-scattering models in galactic and intergalactic space, and (3) the cosmic-ray electron spatial distribution in our galaxy.

SINCE the report of the discovery of an unexpectedly large flux of submillimeter radiation,[1-3] possibly of cosmic origin, efforts have been made to explain the 100-MeV γ radiation of the galaxy[4] in terms of Compton scattering of this infrared radiation by cosmic-ray electrons.[5,6] The possibility of this mechanism producing the diffuse component of cosmic x rays has also been considered.[7,8]

Shivanandan, Houck, and Harwit[1] report the detection of a flux $(5_{-2.5}^{+5})\times10^{-9}$ W cm^{-2} sr^{-1} in the wavelength band 0.4–1.3 mm. The observations are reported to be consistent with isotropy and were repeated.[2] An isotropic flux 1×10^{-9} W cm^{-2} sr^{-1} at 100 μ is also reported.[3] These fluxes represent radiation energy densities of 13 and 2.6 eV cm^{-3}, respectively. By comparison, the 2.7°K universal blackbody microwave radiation[9-11] contains 0.25 eV cm^{-3}. A greybody curve with $T=16$°K and a dilution factor of 6 will fit the 100-μ point, the 0.4–1.3-mm point (effective wavelength 590 μ), and the Rayleigh-Jeans side of the 2.7°K microwave spectrum. Such a greybody flux represents an enormous energy density of 53 eV cm^{-3}. Perhaps the strongest argument against the greybody *continuum* hypothesis has been given by Bortolot, Clauser, and Thaddeus.[12] They placed upper limits on the radiation intensity at $\lambda=1.32$, 0.559, and 0.359 mm by studying interstellar absorption by CN, CH, and CH$^+$. These limits fall below the greybody curve (see Fig. 1). In addition, a direct measurement[11] at 3 mm falls $\sim$3 standard deviations below the greybody curve. However, it is possible for the infrared to be concentrated in sharp lines which avoid the wavelengths examined by the molecular absorption technique. The intensity at $\lambda\sim100\,\mu$ has been questioned[13] but an intensity $\sim8\times10^{-14}$ erg cm^{-2} sr^{-1} sec^{-1} observed[14] at $\lambda\sim900\,\mu$ is in agreement with the 0.4–1.3-mm point of Shivanandan, Houck, and Harwit.

Clark, Garmire, and Kraushaar[4] observed 100-MeV cosmic γ rays with the satellite *OSO*-3. The radiation has the following essential characteristics: (1) an upper limit of $(1.1\pm0.2)\times10^{-4}$ photons cm^{-2} sec^{-1} sr^{-1} for the isotropic intensity of γ rays with energies greater than 100 MeV, and (2) a linear source on the galactic equator with intensity $(5\pm1.5)\times10^{-4}$ photons cm^{-2} sec^{-1} rad^{-1} from the direction of the galactic center and $(2\pm1)\times10^{-4}$ photons cm^{-2} sec^{-1} rad^{-1} from the anticenter. The detector had an angular aperture with half-width 15°. The linear source must have a half-width substantially less than 15°. We find that Compton scattering of the putative galactic infrared radiation accounts for the observed linear intensity and also forces a reinterpretation of the isotropic intensity.

We have computed the solid-angle intensity I_γ (photons cm^{-2} sec^{-1} sr^{-1} keV^{-1}) of the scattered radiation by the method of Felten and Morrison.[15] This gives

$$I_\gamma=\int q_\gamma(\mathbf{r})dL\,,$$

where

$$q_\gamma(\epsilon)=\pi r_0^2 W(m_ec^2/\epsilon_0)^2 I_e(E)/E \tag{1}$$

is the production rate of photons per unit volume–solid-angle–time–energy, $E=(3\epsilon/4\epsilon_0)^{1/2}m_ec^2$, $r_0=e^2/m_ec^2$, ϵ_0 is the average ambient photon energy, W is the energy density of the ambient radiation, ϵ is the scattered photon energy, $I_e(E)$ is the unidirectional, differential intensity of cosmic-ray electrons, and L is the line-of-sight distance.

The cosmic-ray electron spectrum is shown in Fig. 2.[16] We have corrected for solar modulation by multiplying by $\exp(0.4/R\beta)$ for magnetic rigidities $R>R_0=0.5$ GV and by $\exp(0.4/R_0\beta)$ for $R<R_0$, where

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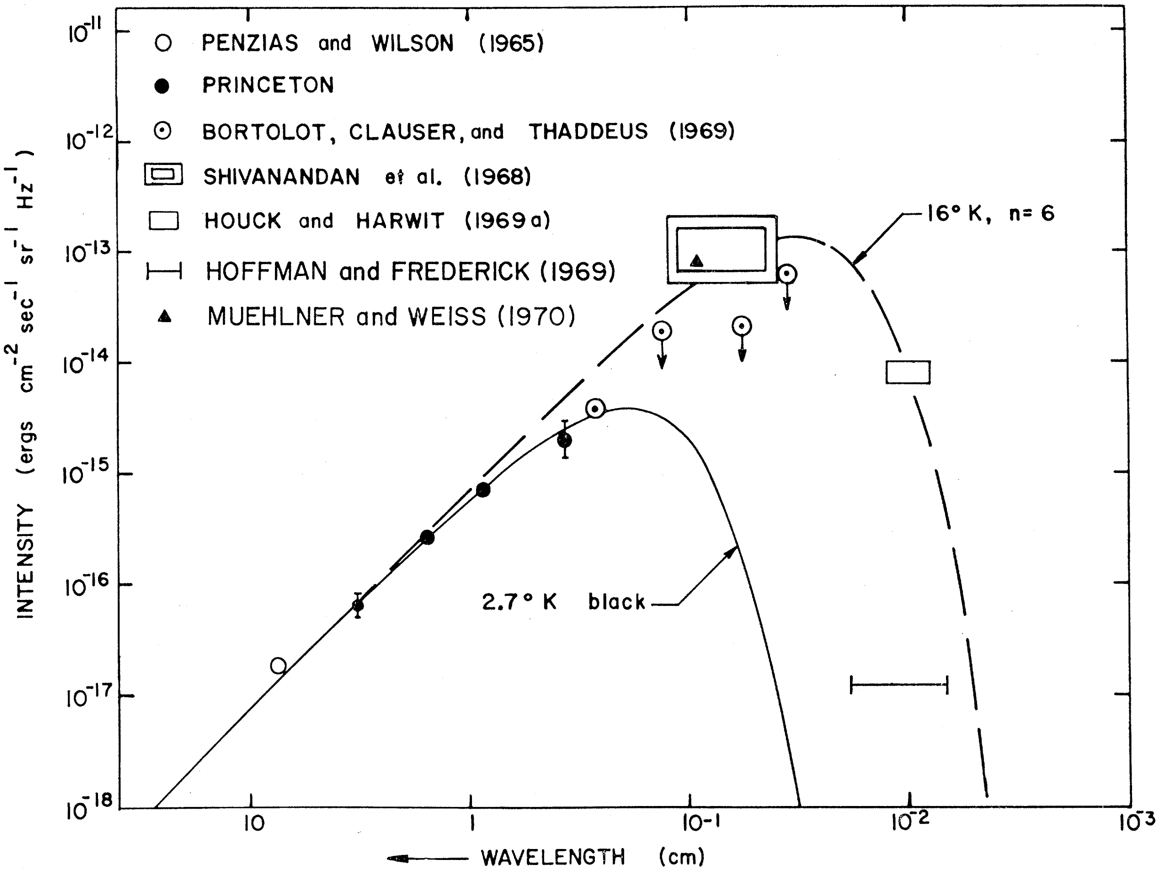

FIG. 1. Cosmic microwave and infrared radiation. The Princeton data are from Refs. 10 and 11.

$\beta=v/c$.[17] In the range ~5–200 GeV the spectrum is approximately[18]

$$I_e(E)=1.26\times10^{-2}E^{-2.62} \quad \text{electrons cm}^{-2}\,\text{sec}^{-1}\,\text{sr}^{-1}\,\text{GeV}^{-1}, \qquad (2)$$

where E is in GeV. There is recent evidence for a possible steepening of the spectrum beyond 200 GeV.[19] Note that below ~1 GeV the demodulated spectrum flattens by more than two powers of energy.

The power-law part of the electron spectrum, Eq. (2), generates a power-law photon spectrum[20] given by

$$I_\gamma(\epsilon)=9\times10^{-19}WL\epsilon_0^{-0.2}\epsilon^{-1.8} \quad \text{photons cm}^{-2}\,\text{sec}^{-1}\,\text{sr}^{-1}\,\text{keV}^{-1}, \qquad (3)$$

where W is in eV cm^{-3}, L in cm, and ϵ and ϵ_0 in eV. For the putative infrared (where $W=13$ and $\epsilon_0=2.1\times10^{-3}$) the integral intensity above 100 MeV is 1.5×10^{-3} photons cm^{-2} sec^{-1} sr^{-1} from the direction of the galactic center, taking $L=23$ kiloparsec (kpc) in that direction.

For directions looking out of the galactic plane, L depends on the half-width z_0 of the disk occupied by cosmic-ray electrons. Analysis of 400-MHz nonthermal continuum radiation indicates that the synchrotron radiation from cosmic-ray electrons (of energies up to a few GeV) comes from a disk of half-width ~400 pc.[21] Thus it is reasonable to expect z_0 to be of order 1 kpc.

Detectors with finite solid angles will see a thin disk as a *linear* source. For a detector with a half-angle θ_0, the linear intensity I_l recorded is given by

$$I_l=(2\theta_0)^{-1}\int\int\int q_\gamma dL d\Omega \text{ photons} \quad \text{cm}^{-2}\,\text{sec}^{-1}\,\textit{radian}^{-1}\,\text{keV}^{-1}.$$

The integration is over the volume of the galactic cosmic-ray electron disk intercepted by the detector's solid angle. For the case of the detector axis lying in the

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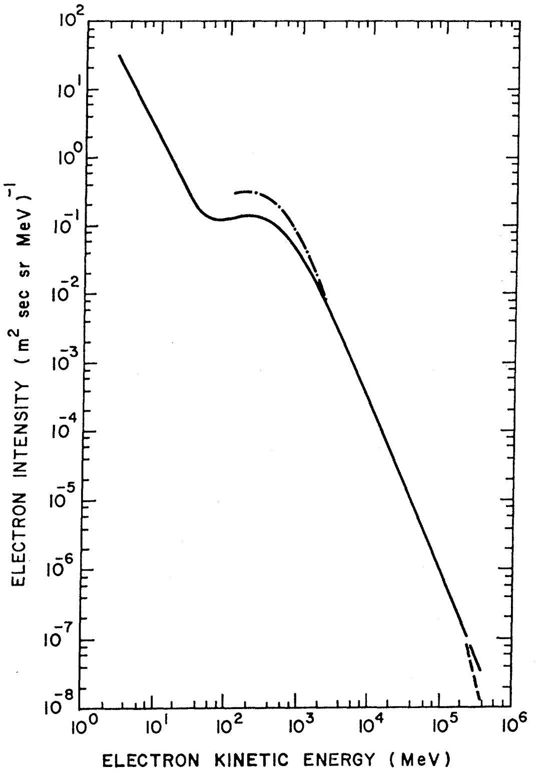

FIG. 2. Cosmic-ray electron spectrum. The solid curve is the spectrum at earth drawn through an extensive body of data reviewed by Meyer (Ref. 16). The dot-dashed curve is the demodulated spectrum mentioned in the text. The dashed curve near 200 GeV is from Ref. 19.

galactic plane, the result is

$$I_l(\epsilon)\simeq\frac{z_0}{L}\left[1.2+2\ln\left(\frac{L\theta_0}{z_0}\right)\right]I_\gamma(\epsilon), \qquad (4)$$

where $\theta_0 \ll 1$ and $z_0 \leq L\theta_0$.

Using Eqs. (3) and (4), we find that for $z_0=1.5$ kpc, Compton scattering of the infrared photons ($W=13$ eV cm^{-3}) produces intensities of 4×10^{-4} photons cm^{-2} sec^{-1} rad^{-1} toward galactic center and 2×10^{-4} photons cm^{-2} sec^{-1} rad^{-1} toward anticenter, for energies ≥ 100 MeV. This compares well with the intensities originally reported[4] from *OSO*-3. Recently, however, these intensities have been revised downward by about a factor of 2.[22] These new intensities require a disk of half-width ~750 pc and are in agreement with results of Fichtel *et al.*[23] but are in some disagreement with observations by Frye *et al.*[24]

Recently, Cooke, Griffiths, and Pounds[25] have found evidence for a linear source of x rays centered on the galactic plane. Looking in the direction $l^{\mathrm{II}}=300°$, they find a linear intensity of ~0.5 photons cm^{-2} sec^{-1} rad^{-1} between 1.4 and 18 keV. They also find the differential spectral index of this diffuse galactic component to be ~ -1.1. With the demodulated spectrum shown in Fig. 2, Eqs. (1) and (4) predict 0.4 photons cm^{-2} sec^{-1} rad^{-1} for the intensity and -1.2 for the spectral index, assuming $z_0=750$ pc and $W=13$ eV cm^{-3}. Thus the infrared seems capable of accounting for both the x rays and the γ rays coming from the galactic disk.

Hoffman and Frederick[26] report an infrared excess in the galactic center, but the solid angle subtended by this excess intensity ($\sim 2°\times6.5°$) is too small to allow a significant enhancement of the γ-ray flux at our position in the galaxy. This is indicated in Fig. 1, where we have plotted the intensity resulting from averaging the reported flux density (1.8×10^{-19} W m^{-2} Hz^{-1}) over the entire sky.

It is instructive to point out exactly how our analysis differs from those of others. Shen[6] assumes an energy-dependent electron spatial distribution. This model contradicts the 1.4- to 18-keV x rays seen by Cooke, Griffiths, and Pounds.[25] The infrared will be scattered to these energies by electrons in the range 0.4–1.3 GeV. Shen's model predicts that electrons in this range will occupy a disk with $z_0\sim5$ kpc, and will have a spectrum which is a continuation of the power-law spectrum of the 10–200-GeV electrons. With this electron spectrum, the predicted intensity for 1.4- to 18-keV x rays is about four times greater than the observed intensity. The predicted spectral index would be -1.7 compared to the observed value -1.1. In addition, the x rays are observed to come from an emission region $\lesssim 6°$ wide normal to the plane. This is inconsistent with a disk of half-thickness 5 kpc.

Cowsik and Pal[5] fail to take any account of the thickness of the electron disk. In comparing with the *OSO*-3 data, they assume that the γ rays are isotropic over the solid angle of the detector, when in fact they are quite anisotropic. In a more recent paper,[8] these authors compare the solid-angle intensity from the direction of the galactic center with the diffuse x rays. This is not a valid comparison since that solid-angle intensity would only be seen by a detector with $\theta_0 \lesssim 2°$ looking toward the galactic center. To compare with the data taken by omnidirectional detectors, the anisotropic intensity produced by the disk must be averaged over the sky, as we have done in Fig. 3.

O'Connell and Verma[7] assume that the electrons occupy a *halo* with average radius ~10 kpc. This type of electron distribution is in conflict with the *linear* photon intensities seen at 100 MeV [4] and at 10 keV.[25] Also, the 100-MeV γ rays that would be produced by a 10-kpc halo would exceed the original upper limit[4] for the

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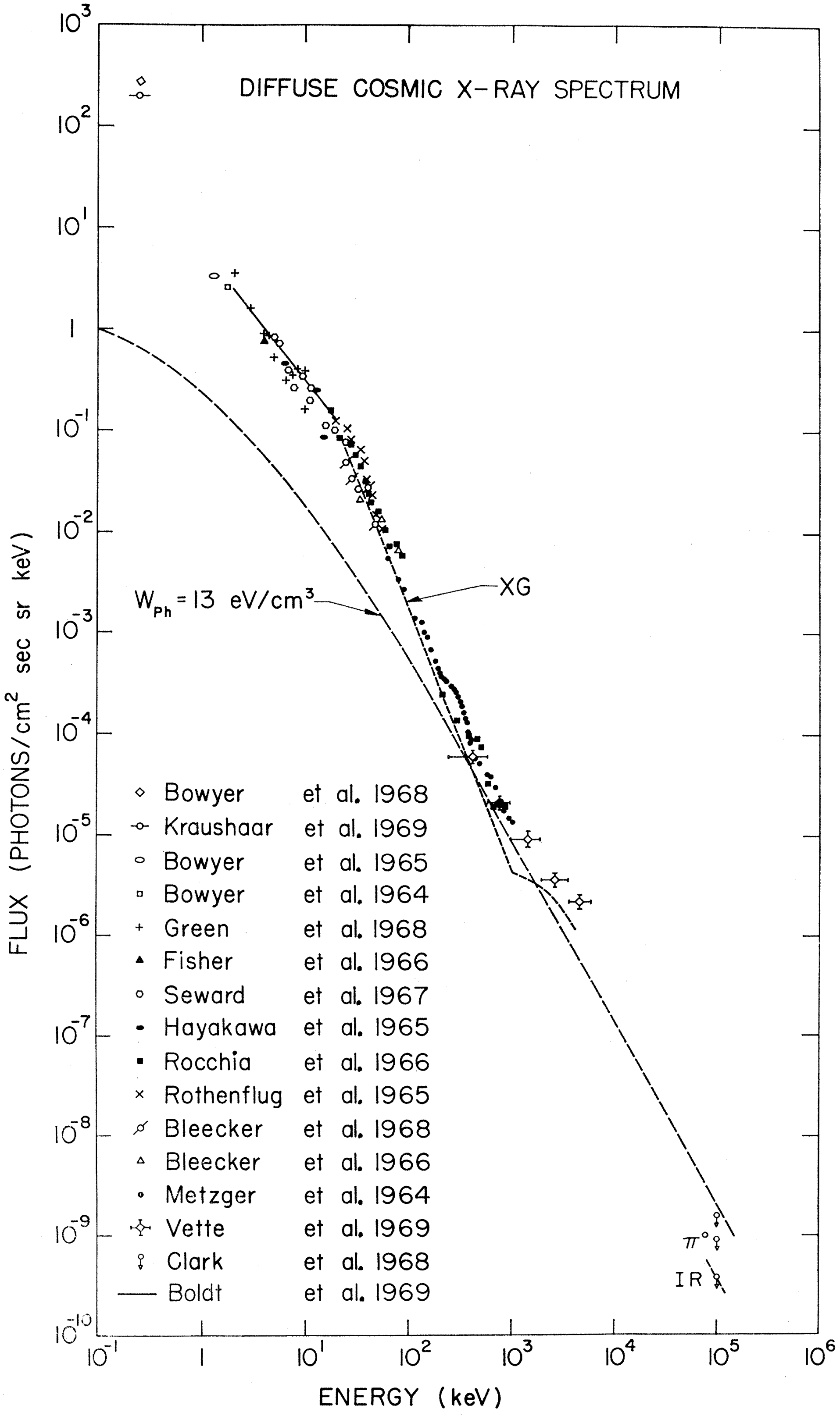

FIG. 3. Cosmic x-ray spectrum. The data are from Refs. 4 and 27. The curve labeled $W_{ph} = 13$ eV/cm³ represents the intensity produced by galactic Compton scattering of the infrared radiation, as seen by an omnidirectional detector. Curve "XG" is the result of subtracting this curve from the observed x-ray spectrum. The points at 100 MeV were plotted assuming a differential spectral index of −3. The points π^0 and IR are modifications of the original upper limit, as explained in the text.

intensity toward the galactic pole by a factor of 5 if $W=13$ eV cm^{-3}, and by a factor of 10 if $W=23$ eV cm^{-3}, as these authors assumed.

We also disagree with O'Connell and Verma with regard to their suggestion that the infrared may explain the *diffuse* x rays. Figure 3 shows the observed diffuse x-ray spectrum.[4,27] The curve labeled $W_{\text{ph}}=13$ eV/cm^3 represents the x-ray intensity $\langle I_\gamma \rangle$ produced by this mechanism with $z_0=1.5$ kpc as seen by an omnidirectional detector, given by $(4\pi)^{-1}\int\int\int q_\gamma dL d\Omega$, where the integration is over the entire volume of the electron disk. As can be seen, the resulting x rays have a spectrum which is too flat to agree with the observed diffuse x-ray spectrum. This process can, however, produce a large fraction of the x rays observed near 0.5 MeV. We note that near this energy all the observations were made with omnidirectional detectors (Rocchia *et al.*, Metzger *et al.*, and Vette *et al.*, in Ref. 27). Subtracting the galactic contribution from the observed x rays, we then obtain an extragalactic x-ray spectrum that exhibits a distinct "kink" near 1 MeV (see curve labeled "XG" in Fig. 3). The resultant spectrum above 1 MeV resembles the red-shifted γ-ray spectrum arising from decay of π^0 mesons generated by cosmic-ray interactions.[28]

At 100 MeV we have plotted the *OSO*-3 upper limit to the diffuse γ-ray intensity. Clark *et al.*[4] arrived at this value by attributing the minimum counting rate of the detector to an isotropic extragalactic intensity. However, if the linear galactic source is generated in a uniform disk of finite width, it will also contribute to the intensity coming from the galactic pole. Given the observed intensity of the *linear* source, the counting rate in the direction of the galactic pole depends solely on z_0; it is independent of the mechanism producing the linear source. We have computed the galactic contribution to the polar counting rate for two cases: $z_0=130$ pc, the half-width of the interstellar gas disk,[29] corresponding to the (galactic) π^0 decay mechanism[30]; and $z_0=1.5$ kpc, corresponding to the infrared mechanism. The residual (extragalactic) intensity is then obtained by subtracting this galactic component from the *OSO*-3 upper limit. The results are shown in Fig. 3. We find that for either the π^0 or the infrared hypothesis most of the observed pole component at 100 MeV is galactic. For example, for the infrared hypothesis any extragalactic component must be at least five times smaller than the upper limit set by Clark *et al.* Using the revised *OSO*-3 intensities,[22] all three points plotted at 100 MeV in Fig. 3 should be moved downward by the same factor (about 2).

There have been many attempts[31–33] to explain the diffuse x-ray spectrum as the result of Compton scattering of *inter*galactic electrons by the 2.7°K blackbody radiation. We wish merely to call attention to the fact that, writing the x-ray spectrum as $\epsilon^{-\alpha}$, the index α is observed to be ~ 1.5 for $\epsilon<20$ keV and $\alpha\simeq 2.4$ for 20 keV$<\epsilon<1$ MeV. If the x rays arise in Compton emission and the intergalactic electrons have an average spectrum E^{-m}, then $\alpha=\frac{1}{2}(m+1)$. Thus, the *observed* "break" in the x-ray spectrum $\Delta\alpha\sim 1$ implies a "break" in the average electron spectrum $\Delta m=2\Delta\alpha\sim 2$. (This break should be located at $E\sim 3$ GeV.) No analysis to date incorporates this large a break in the electron spectrum.

Note added in proof. At the American Physical Society meeting, Washington, D. C., 29 April 1970, J. R. Houck announced a revised infrared flux, implying $W=6$ eV cm^{-3}. However, G. P. Garmire announced that the *OSO*-3 measurements of γ rays above 100 MeV had also been revised downward, to 12×10^{-5} photons cm^{-2} sec^{-1} rad^{-1} from the galactic center, 4×10^{-5} cm^{-2} sec^{-1} rad^{-1} from the anticenter, and $<3\times10^{-5}$ cm^{-2} sec^{-1} sr^{-1} from the poles. Using $W=6$ eV cm^{-3} and $Z_0=500$ pc, Compton scattering produces 9.5×10^{-5} photons cm^{-2} sec^{-1} rad^{-1} from the galactic center, 4.5×10^{-5} cm^{-2} sec^{-1} rad^{-1} from the anticenter, and a minimum intensity from the galactic poles of 1.5×10^{-5} cm^{-2} sec^{-1} sr^{-1}. The predicted x-ray intensity between 1.4 and 18 keV is now about a factor of 4 below the Cooke *et al.*[25] observation. Thus, Compton scattering of the infrared can explain the 100-MeV γ-ray observations, but not the low-energy x-ray observations. Finally, the curve "$W_{\text{ph}}=13$ eV/cm^3" in Fig. 3 should be moved downward by a factor of about 5, making the "XG" curve unnecessary.

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