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Molecular Hydrogen in the Galaxy and Galactic Gamma Rays

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ABSTRACT

Recent surveys of 2.6 mm CO emission and 100 MeV γ-radiation in the ga;actic plane reveal a striking correlation suggesting that both emissions may be primarily proportional to the line-of-sight column density of H_2 in the inner galaxy. Both the γ-ray and CO data suggest a prominent ring or arm consisting of cool clouds of H_2 at a galactocentric distance of $\sim$ 5 kpc with a mean density of $\sim$ 4 atoms/cm^3. Estimates are made of column densities of H_2 at $\ell^{II} = 0^o$. The estimates at 0^o are compared with estimates from infrared and x-ray absorption measurements. These estimates are all consistent and indicate that H_2 is far more abundant than HI in the inner galaxy and is the key to a more satisfactory explanation of the γ-ray observations than previous suggestions. The importance of H_2 in understanding galactic γ-ray observations is also reflected in the correlation of galactic latitude distribution of γ-rays and dense dust clouds. This picture suggests that only small or moderate enhancements in the cosmic-ray flux in the inner galaxy would be consistent with the γ-ray observations. The cosmic-ray distribution suggested by the calculations is similar to that of galactic supernova remnants, suggesting a galactic origin for most cosmic rays.

A detailed calculation of the γ-ray flux distribution in the 0^o to 180^o range using the CO data to obtain the average distribution of molecular clouds in the galaxy shows that most of the enhancement in the inner galaxy is due to π^o-decay radiation and the the 5 kpc ring plays a major role. Detailed agreement with the γ-ray data is obtained with the additional inclusion of contributions from bremsstrahlung and Compton radiation of secondary electrons and Compton radiation from the intense radiation field near the galactic center.

MOLECULAR HYDROGEN IN THE GALAXY AND GALACTIC GAMMA-RAYS

1. Introduction

Molecular hydrogen has long been suspected to be an important component of interstellar gas because it is the most stable low-temperature form of the most abundant element in the galaxy. A review of the role of molecules in interstellar space has been given by Solomon (1973). H_2 is expected to be the predominant form of hydrogen in cool clouds of sufficient density (Solomon and Wickramasinghe 1969, Hollenback and Salpeter 1971, Hollenbach, Werner and Salpeter 1971). However, despite its abundance, it is difficult to measure its galactic distribution directly. The detection of Lyman absorption bands from H_2 was reported by Carruthers (1970) and strong absorption lines from interstellar H_2 in almost all nearby clouds observed have been seen in the UV spectra of reddened stars by the Copernicus satellite (Spitzer, et al. 1973). However, UV observations of H_2 at distances greater than 1kpc and in any cloud with greater than 2 magnitudes of visual extinction are not feasible because of the large extinction of UV radiation by interstellar dust. Also, because the hydrogen molecule has no permanent dipole moment, no dipole radiation is expected from H_2 and quadrupole vibration-rotation features, while potentially detectable in the infrared in dark clouds, are inherently very weak. The direct UV observations of Spitzer et al. (1973) have indicated that H_2 is a significant component of the interstellar gas; and because the hot young stars that delineate the spiral features of our galaxy form from cool dense clouds of primarily molecular hydrogen, it is important to determine the large scale distribution of H_2 in the galaxy in order to understand galactic structure. Results from two promising methods for indirectly studying the galactic distribution of H_2 are discussed here, viz., recent galactic surveys of 100 MeV γ-radiation and 2.6mm radio line emission from the $J = 1 \rightarrow 0$ transition of CO molecules. To these surveys, which reflect the extent and distribution of H_2 in the plane of galaxy, we will add corroborating information on the amount and latitude distribution of gas in the direction of the galactic center supplied by x-ray, optical, and infrared absorption measurements.

2. The Recent SAS-2 Gamma-Ray Galactic Longitude Observations

Fichtel et al. (1975) have recently reported the results of a sky survey made of 100 MeV γ-rays using a spark chamber aboard the SAS-2 satellite. Their results on the γ-ray flux measured within $\pm 10^{\circ}$ of the galactic plane are shown in figure 1. While it is clear that the general intensity of the flux in the half-plane away from the galactic center can be understood as arising from the decay of π°-mesons produced in cosmic-ray interactions primarily with atomic hydrogen (based on the production rate calculated by Stecker, 1970, 1973), the large intensity particularly for the 60° longitude region about the galactic center cannot be understood so simply. Indeed, the similar galactic longitude distribution observed by OSO-3 detector was also noted to be distinctly uncorrelated with the 21 cm distribution by Clark et al. (1970). The OSO-3 result implied an increase in cosmic-rays, unseen gas or both in the inner galaxy, and it was suggested by Stecker (1969, 1971) and Stecher and Stecker (1970) that molecular hydrogen unseen in 21 cm surveys could account for a large part of the γ-ray enhancement in the inner galaxy. Black and Fazio (1974) have recently explored the possibility of dark molecular hydrogen clouds being γ-ray sources.[1]

The SAS-2 data obtained by Fichtel et al. (1975) shows pronounced peaks near 180° in the direction of the Crab nebula and near 270° in the direction of Vela X. These sources can be separated from a discussion of the general diffuse galactic radiation and they have been discussed by Fichtel, et al. (1975). The general trend of the remaining flux observed by SAS-2 strengthens the case made by the earlier OSO-3 data that neither the distribution nor the absolute flux of γ-radiation can be explained based on the 21 cm data. A model has been proposed by Bignami and Fichtel (1974) and Bignami et al. (1975) based on producing large enhancements at the locations of arms mapped by 21 cm surveys by postulating higher gas densities than are seen in 21 cm as well as higher cosmic-ray intensities in those locations. We feel that the galactic γ-ray observations can be better understood by using other observations in addition to 21 cm surveys to determine the role of H_2 clouds invisible in 21 cm emission.

3. The Galactic CO Distribution and the Molecular Ring at ∿5kpc

A survey of the galactic longitude distribution of CO emission in the galactic plane has recently been made by Scoville and Solomon (1975).

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[1] Possible enhancement in the galactic cosmic-ray flux in the inner galaxy were also explored by Ginzburg and Khazan (1972) and Strong et al. (1973). The initially reported SAS-2 results (Kniffen, et al. 1973) were noted by Stecker, et al. (1974) and Puget and Stecker (1974) to imply a particularly pronounced enhancement in the γ-ray emissivity in a toroidal region about 5kpc from the galactic center and a model was suggested by them for enhancing the galactic cosmic ray flux in that region by first order Fermi acceleration. Possible correlations with the galactic magnetic field strength were recently studied by Schlicheiser and Thielheim (1974). Other discussions of the origin of galactic γ-rays have been given by Dodds et al. (1974) and by Cowsik and Voges and by Paul, Casse and Cesarsky in the same proceedings. For further discussion see the recent review by Stecker (1975).

The importance of this survey in understanding the distribution of H_2 in the galaxy lies in the fact that CO is an excellent tracer of H_2. The relationship between H_2 and CO in molecular clouds, based on the fact that the most important source of CO excitation in these clouds is by collisions with H_2 and radiative trapping, has recently been discussed by Scoville and Solomon (1975) and Goldreich and Kwan (1974). The density ratio N_{H_2}/N_{CO} is expected to be roughly constant and of order 10^4.

Scoville and Solomon (1975) have used the velocity profile data obtained in their CO survey in conjunction with the Schmidt (1965) rotational model of the galaxy to determine the mean distribution of CO in the galaxy as a function of galactocentric distance for distances greater than 2.6kpc This distribution shows a broad peak with a maximum near 5kpc which Scoville and Solomon have concluded indicates a ring of H_2 clouds in this region. The connection between this feature and the γ-ray emission ring at $\sim$5kpc discussed by Puget and Stecker (1974)[2] prompted Solomon and Stecker (1974) to suggest that the γ-ray data also provide evidence for the molecular cloud ring near 5kpc. Coincidently, there is also a similar distribution and peak in the HII regions of the galaxy (Metzger 1970). This may be understood to be the effect of hot young stars being formed out of dense molecular clouds in this ring. The formation of such a prominent molecular ring poses an intriguing problem for galactic structure theory. Such a large scale region of relatively cool high-density clouds may be the result of a shock front and thus provide a key to understanding the structure of the inner galaxy.

The γ-ray emissivity measurements from SAS-2 can be used to place an upper limit on the H_2 density at 5kpc. Puget and Stecker (1974) have

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[2] Based on the data as given by Kniffen, et al. (1973).

estimated the emissivity ratio

$$\frac{Q_\gamma(5\mathrm{kpc})}{Q_\gamma(10\mathrm{kpc})} \simeq 11 \pm 2 \qquad (1)$$

which is proportional to the ratio of the products of total baryon density and cosmic ray intensity at 5 and 10 kpc respectively. Assuming that the ratio of cosmic ray intensities $I_{CR}(5\mathrm{kpc})/I_{CR}(10\mathrm{kpc}) \geq 1$ (Puget and Stecker 1974) we find that N_{H_2} (5kpc) $\lesssim$ (5$\pm$1) molecules/cm^3. This result, however, only includes the statistical errors in the SAS fluxes and the error in the analysis is probably underestimated. Strong (to be published) has obtained a similar result to that of Puget and Stecker. The CO data of Scoville and Solomon (1975) give an estimated H_2 density in the 5kpc region of between 1 and 10 molecules/cm^3. The γ-ray upper limit is thus consistent with the range allowed by the CO observations.

4. Molecular Hydrogen and Total Column Densities in the Direction $\ell=0^\circ$

By using the distribution of CO emission given by Scoville and Solomon (1975) one can estimate the amount of molecular hydrogen at $\ell=0^\circ$ excluding the galactic nuclear region. The result is $1.5 \times 10^{22} \leq \left\langle 2N_{H_2} \right\rangle \leq 15 \times 10^{22}$ cm^{-2}. This number can also be estimated from measurements of x-ray and infrared absorption measurements in the direction of the galactic nucleus (Ryter, Cesarsky and Audouze, 1975).

X-rays and infrared radiation are moderately attenuated when travelling through several kpc in the galaxy and this attenuation, in both cases, is due primarily to carbon, nitrogen and oxygen. The infrared is attenuated by interstellar grains and the x-rays are attenuated by photoelectric absorption. Thus the amount of matter on the line of sight to a source with a known (or calculated) energy spectrum can be deduced using the cosmic abundance ratios.

X-ray absorption in front of the galactic center source, GCX, has been measured by Tucker, et al. (1973) and the amount of "equivalent atomic" hydrogen along the line of sight has been given as $\langle N_H \rangle = (9 \pm 2) \times 10^{22}$ atoms/cm^2 based on the cross sections of Brown and Gould (1970) assuming that the universal abundances hold and that all the hydrogen is atomic. However, as we have seen, this value is almost an order of magnitude higher than $\langle N_{HI} \rangle$ given in the 21 cm surveys and a strong argument may be made that most of the hydrogen is in molecular form. The photoelectric cross section per H atom for H_2 molecules is about an order of magnitude larger than that for atomic hydrogen due to the higher effective atomic number, Z. Although the main x-ray absorption comes from C, N and O, assuming that the hydrogen is in molecular form increases the absorption rate by about 30% at a photon energy of 1 KeV. One then gets the estimate from x-ray absorption of $\langle 2N_{H_2} + N_{HI} \rangle = 6.7 \times 10^{22}$ cm^{-2} (Ryter, Cesarsky and Audouze, 1975).

This column density can also be estimated allowing for the possibility that the CNO abundance relative to hydrogen may increase in the direction of the galactic center. Spiral galaxies in general seem to exhibit abundance gradients with higher relative content of CNO in the central region (Peimbert 1968, McClure 1969, Searle 1971, Benvenuti, et al. 1973). Taking as typical figures C and O enriched by ~ 1.5, we obtain the estimate $\langle 2N_{H_2} + N_{HI} \rangle = 5.3 \times 10^{22}$ cm^{-2}.

Infrared absorption in the line of sight to the galactic center has been measured at 0.35, 0.90, 1.65, 2.2 and 3.4 μ by Spinrad et al. (1971). Using a standard reddening curve and postulating a thermal spectrum for the infrared source at the galactic center, a color excess of $E_{B-V} = 9.5^{+2}_{-1}$ magnitudes is deduced with an implied visual extinction $A_V = 29$ magnitudes.

Using the relation

$$N_H \approx 7\text{x}10^{21}\ E_{B-V}\ \text{cm}^{-2} \qquad (2)$$

(Jenkins and Savage 1974, Gorenstein 1974, Ryter et al. 1975), the amount of matter on the line of sight to the galactic center is estimated to be $\langle N_{HI} + 2N_{H_2}\rangle = 6.5\text{x}10^{21}\ \text{cm}^{-2}$.

All of the about methods give consistent results which are summarized in table 1.

Table 1. Column Densities of Hydrogen at $\ell=0^{\circ}$ Excluding the Galactic Nucleus (x10^{-22}) (cm^{-2})

$\langle N_{HI}\rangle$ from 21 cm radio	$\gtrsim$0.6-1.5	Daltabuit and Meyer (1972)
	$\sim$2	Kerr and Westerhout (1965)
	$\gtrsim$1.2	Clark (1965)
$\langle 2N_{H_2}\rangle$ from CO	1.5 to 15	Scoville and Solomon (1975) and this work
$\langle 2N_{H_2} + N_{HI}\rangle$ from SAS-2 γ-ray flux	$\lesssim$(11.5$\pm$2)	this work ($I_{CR} \gtrsim I_{\odot}$)
$\langle 2N_{H_2} + N_{HI}\rangle$ from x-ray absorption	5.3 to 6.7	this work and Ryter, et al. (1975)
$\langle 2N_{H_2} + N_{HI}\rangle$ from IR absorption	6.5	Ryter, et al. (1975)

Scoville, Solomon and Jefferts (1974) estimate the total mass of the molecular disk at the galactic center to be

$$4\text{x}10^{7} \lesssim (M_{GC}/M_{\odot}) \lesssim 10^{8}$$

Such a mass would yield a contribution to the measured γ-ray flux at $\ell=0^\circ$ of

$$\Delta I_{\gamma,GC} = \frac{1}{\Delta\ell} (1.3\text{x}10^{-6})\, R_{pc}^{-2}\, (M_{GC}/M_\odot)\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{rad}^{-1} \qquad (3)$$

assuming I_{CR} (GAL. CEN.) = I_{CR} (10kpc) (Ginzburg and Khazan 1972, Stecker 1973, Black and Fazio 1974). This yields an estimated flux in the range

$$0.6\text{x}10^{-5} \lesssim \Delta I_{\gamma,GC} \lesssim 1.5\text{x}10^{-5}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{rad}^{-1}$$

5. Calculations of the Galactic Gamma Ray Flux as a Function of Longitude

In performing numerical calculations of the longitude distribution of the galactic γ-ray flux from π^0 decay, we have used the survey of Scoville and Solomon (1975) to obtain the <u>relative</u> distribution of molecular hydrogen in the galaxy as a function of galactocentric distance ϖ and have normalized to a total column density in the direction of the galactic center using the X-ray and infrared absorption measurements shown in table 1 and which are consistent with the values from other measurements given in the table which are more uncertain. The contribution from atomic hydrogen was estimated based on the numbers given by Kerr and Westerhout (1965) and Westerhout (1970). The γ-ray longitude distribution is given by the relation

$$I_\gamma(\ell) = \frac{q_\odot}{4\pi} \int_{-10^\circ}^{+10^\circ} db \int_0^{h\cot b} ds \left(\frac{J(\varpi)}{J_\odot}\right) \left[n_{HI}(\varpi) + n_{H_2}(\varpi)\right] \qquad (4)$$

where b is galactic latitude, h is the half-thickness of the galactic plane taken to be 110 pc in the inner galaxy[3], $q_\odot = 1.3 \times 10^{-25}\ s^{-1}$ is the specific γ-ray luminosity from π^0 decay, electron bremsstrahlung and Compton radiation above 100 MeV in the solar galactic neighborhood[4], s is heliocentric distance and

$$\varpi = (\varpi_\odot^2 + s^2 - 2\varpi_\odot s \cos \ell)^{\frac{1}{2}} \ . \qquad (5)$$

The quantity $J_\odot$ is the cosmic ray intensity in the local galactic neighborhood and $J(\varpi)$ is the cosmic ray intensity assumed to be a function of galactocentric distance. $n_{HI}(\varpi)$ is the neutral hydrogen density obtained from 21 cm measurements and $n_{H_2}(\varpi)$ is the density of H_2 inferred from the CO survey normalized so that

$$N_{GC,\odot} \equiv (N_{H_2} + N_{HI})_{G.C,\odot} = \int_0^{\varpi_\odot} d\varpi \left[n_{HI}(\varpi) + N_{H_2}(\varpi)\right] \qquad (6)$$

$$= (7 \pm 1.5) \times 10^{22}\ cm^{-2}.$$

For the purpose of the calculations to estimate the effect of cosmic ray enhancements in the galaxy, it was assumed that such enhancements may be correlated with the gas distribution so that

$$\frac{J(\varpi)}{J_\odot} = \left[\frac{n_{HI}(\varpi) + n_{H_2}(\varpi)}{n_{HI,\odot} + n_{H_{2,\odot}}}\right]^\alpha \qquad (7)$$

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[3] Allowance for variation of h, particularly outside 10kpc was made by adjustin the values of $n(\tilde{\omega})$.

[4] Above 100 MeV, $q_{\pi^0} \simeq 1.1 \times 10^{-25}\ s^{-1}$, (Stecker 1970) $q_{brems} \simeq 0.1 \times 10^{-25}\ s^{-1}$ Stecker (1971) and $q_{Compton} \simeq 0.06 \times 10^{-25}\ s^{-1}$ (Stecker 1975). In the outer galaxy, the starlight gradient is assumed to vary like the total gas gradient, an approximation which doesn't affect the calculations very much as long as Compton radiation is such a minor component of the total flux.

where, from dynamical considerations, the exponent $\alpha \leq 1$.[5]

We have calculated $I_\gamma(\ell)$ for two cases. In case I a constant cosmic ray flux in the galaxy was assumed ($\alpha=0$) in order to determine the effect of gas density contrast alone on the γ-ray longitude distribution. For this case, a value of $N_{GC,\odot} = 8.5 \times 10^{22}$ cm^{-2} was taken corresponding to the upper limit on the total column density implied by the infrared and X-ray absorption measurements. In case II, it was assumed that $N_{GC,\odot} = 7 \times 10^{22}$ cm^{-2} and $\alpha=0.3$ corresponding to an increase of about a factor of 2 in the cosmic ray flux in the 5kpc region as indicated by studies of the supernova remnant distribution in the galaxy (Ilovaisky and Lequeux 1972, Kodaira 1974), scale height measurements (Jackson and Kellman 1974) and synchrotron radiation measurements (Webber 1968, Price 1974, Daniel and Stephens 1975). We consider case II to be the situation most consistent with all the measurements we have to date on the total gas distribution and cosmic ray distribution in the galaxy. It corresponds to a mean value for the total gas density of ∿1 atom/cm^3 at 10 kpc of which ∿40 percent is in molecular form. This agrees with the values given by Spitzer, et al. (1973) from measurements of rotational UV absorption lines of H_2 and those given by Jenkins and Savage (1974) for Lyman α lines of HI. In the 5kpc region, case II corresponds to a volume-averaged total density of ∿5 atoms/cm^3 of which ∿80 percent would be in molecular form.

The results of the numerical calculations for cases I and II are shown in Figure 1 together with the flux distribution given by Fichtel et al. (1975) from the SAS-2 observations for the half-plane from 0° to 180° over which the CO measurements of Scoville and Solomon (1975) can be applied.

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[5] Bignami et al. (1975) using a different gas distribution, have assumed $\alpha=1$ corresponding to cosmic-rays varying linearly with gas density.

These results indicate that most of the observed γ-ray enhancement at low longitudes is primarily a result of increased gas density and that the molecular ring near 5kpc plays an important role in accounting for this increase.

Cosmic rays are limited to a small variation over the galactic disk given by $0.2 \lesssim \alpha \lesssim 0.5$ derived from the limits on the amount and distribution of gas implied by the observations discussed in section 4. Thus we conclude that the cosmic rays cannot vary linearly with the gas density over all segments of the galaxy, nor do they appear to be uniformly distributed. The similarity of the cosmic-ray distribution and the supernova remnant distribution[6] suggests a galactic, supernova origin for most cosmic rays (Ginzburg and Syrovatskii 1963).

The general level of the flux between 90° and 180° is consistent with the assumption of an almost pure π^0 decay origin of γ-rays locally and in the outer galaxy when the effect of molecular hydrogen is included, supporting the calculations of Stecker (1973)[7]. The minimum between 60° and 70° and the maximum between 80° and 90° are reproduced, but with insufficient contrast as is also the case with the calculations of Bignami et al. (1975). This may be understood as due to "hot spots" from local concentrations of gas in clouds within the Orion arm rather than a general large-scale arm feature itself. Evidence for the clumpiness of local gas has been obtained from studies of interstellar reddening (FitzGerald 1968), the ultraviolet observations from Copernicus (Spitzer et al. 1974, Jenkins and Savage 1974) and the CO observations of Scoville and Solomon (1975) as well as many other

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[6] Both peak at ∿5kpc at about twice the local value.

[7] The calculations appear to be a bit high in this region, possibly indicating that cosmic rays drop off faster than gas in the outer galaxy, again consistent with supernova origin. This point is also noted in a recent calculation by D. Dodds, A. W. Strong and A. W. Wolfendale (preprint).

molecular observations by other workers. The half-plane from 180° to 360° is even more riddled with "hot spots", some of which are undoubtedly associated with local cloud complexes (Puget 1975, preprint), and possibly supernova remnants (Fichtel et al. 1975).

The results shown in figure 1 indicate that the character of the longitude distribution of galactic γ-radiation corresponds well with the overall density distribution in the galaxy implied by the CO and 21 cm measurements and that this distribution has a broad maximum in the 5 to 6 kpc region. Higher frequency modulations by spiral arms do not appear to us to play a significant role in determining the galactic γ-ray distribution within the statistical errors and 5° resolution of the SAS-2 data, at least for the half plane analyzed here using the CO data.

Thus, the galactic gas seems to have a large-scale superstructure modulated by spiral arm perturbations similar to that seen in M31 in 21 cm emission (Guibert 1974) and in our own galaxy in nonthermal radio emission (Price 1974), and it appears to be the superstructure which determines the character of the SAS-2 longitude distribution. The molecular cloud distribution appears to be steeper and more localized than the HI distribution to the ring of maximum gas density associated with the HII maximum as is the case in M81 (Gottesman and Weliachew 1975).

The calculations shown in figure 1 deviate from the observations for $\ell < 40^\circ$. This is due to the fact that the effect of increased production of secondary electrons and positrons, particularly in the 5-6 kpc region and the effect of high radiation fields in producing Compton radiation in the galactic nuclear region have not been included. Secondary electrons make up approximately 17% of the total electron flux above 100 MeV locally (Daniel and Stephens 1975) but their production rate goes up by an order of magnitude in the 5-6 kpc region because it scales like the γ-ray production rate, both processes being the result of cosmic-ray π-meson decay. When this effect is included in the calculations and the effect of the enhanced radiation field in producing Compton radiation in the galacti nuclear region is also taken into account, based on the estimates of Dodds et al. (1974), the total flux distribution shown in figure 2 is obtained. This distribution is compared in figure 2 with the range of the measurements obtained from SAS-2. The agreement between the calculations and the observations can be seen to be excellent. It can also be seen that the total contribution from bremsstrahlung and Compton interactions of both primary and secondary electrons to the galactic γ-ray flux in the central region is of the order of 30 percent, in agreement with the estimates made by Stecker et al. (1974) using the observed γ-ray energy spectrum obtained by SAS-2.

6. Gamma-ray Latitude Distribution and Associated Line of Sight Reddening

In addition to the γ-ray longitude distribution measurements reported by Fichtel et al. (1975), a galactic latitude distribution was also obtained. This distribution shows an asymmetry with respect to the galactic plane with more flux coming from positive galactic latitudes in the case of moderat latitudes $6^{\circ} \leq |b| \leq 30^{\circ}$. The 21 cm measurements of neutral hydrogen summarized by Daltabuit and Meyer (1972) show less asymmetry of this kind. Thus here, as in the case of the longitude distributions, no detailed correlation is evident between the HI density and the γ-ray flux. However, another correlation does present itself.

Recent studies of the reddening of globular clusters by Kron and Guetter (1973) show that clusters at negative latitudes are less reddened than those at positive latitudes. Thus, the observed γ-ray flux asymmetry in the center direction appears to be associated with the fact that there is a greater number of dense clouds containing dust at positive latitudes than at negative ones in that direction. This is also borne out in the survey of Knapp and Kerr (1974). Such reddening may be associated with the location of Gould's extinction belt (Lynds 1962, Heiles and Jenkins, in preparation) and a possible correlation between moderate-latitude γ-rays and Gould's belt was noted by Fichtel et al. (1975) in their discussion of the γ-ray latitude distribution. All of this can be understood in the context of section 4 where it was pointed out that UV, X-ray infrared absorption measurements indicate that the <u>total</u> column density of gas is proportional to the reddening in a given direction and that in the direction of highly reddened objects most of the hydrogen may well be in molecular form as expected in dense dust clouds and as is indicated by only a partial correlation with 21 cm emission. The data of Knapp and Kerr (1974) in the region of the sky located between $\ell = 345^\circ$ and 30° and between $b = 10^\circ$ and 30° can be used to evaluate the average reddening and HI column density at $b = 20^\circ$. We obtain $\langle E_{B-V}(20^\circ)\rangle = 0.26$ mag and $\langle N_H(20^\circ)\rangle = 9.7 \times 10^{20}$ H atoms cm^{-2}. Postulating the same cosmic ray density as observed locally we find from the reddening and relation (2) a gamma-ray flux of 2.2×10^{-5} cm^{-2} s^{-1} sr^{-1} which compares favorably with the flux reported by Fichtel et al. (1975) observed at $b = 20^o$ of 2 to 2.5×10^{-5} cm^{-2} s^{-1} sr^{-1}. However, the flux estimated from the HI-column density is only 1.4×10^{-5} cm^{-2} sec^{-1} sr^{-1} which is particularly significant in this case because at high galactic latitudes the 21 cm emission line is not optically thick (Knapp and Kerr 1974). Thus, the situation with regard to the latitude distribution of galactic gamma-rays is analogous to that of the longitude distribution and can be better understood by taking account of H_2 unseen in 21 cm surveys of HI gas.

8. Summary

We have shown how the galactic γ-ray emission, which is proportional to the total density of gas in the galaxy, is correlated with the galactic CO distribution, CO being a tracer of interstellar H_2. We have also shown that UV, X-ray and infrared absorption measurements, which also appear to be correlated with total interstellar gas density indicate, along with the γ-ray measurements and CO measurements, that there are large amounts of H_2 in dense clouds in the inner 7 kpc of the galaxy much in excess of the HI seen in 21 cm surveys. Thus, in the inner galaxy, 21 cm surveys do not appear to give a true indication of the amount and distribution of interstellar hydrogen because they do not indicate the presence of large amounts of H_2. The correlation between the galactic latitude distributions of dense clouds (predominantly H_2) and γ-ray emission also bear this out. We thus arrive at a more satisfactory explanation of the galactic γ-ray emission than those suggested previously because it is based upon a wide range of empirical data involving the whole range of the electromagnetic spectrum from radio to γ-ray wavelengths and thus minimizes model building with arbitrary assumptions. The consistent picture which emerges highlights the significant role of H_2 in understanding galactic structure and emphasizes the importance of the knowledge to be gained by future advances in galactic γ-ray surveys and CO surveys in understanding galactic dynamics. A particular feature discussed here is the existence of a prominent ring or arm of H_2 clouds at $\sim$5 kpc. The fact that this region corresponds to one of maximal amounts of HII in the galaxy suggests that this ring of dense clouds is the cite of most active star formation. A shock-wave origin of the 5 kpc molecular ring is speculated on.

The picture of the galactic gas distribution presented here suggests that only small or moderate enhancements in the galactic cosmic-ray flux distribution are consistent with the γ-ray observations. The distribution of cosmic rays suggested by the calculations is similar to that of galactic supernova remnants, peaking in the 5 kpc region at about twice the local value, supporting the galactic supernova hypothesis for the origin of most cosmic rays.

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Figure 1. Comparison of the results of our numerical calculations with the SAS-2 data of Fichtel et al. (1975) for the two cases discussed in the text and neglecting the contributions from increased secondary electron production and radiation density in the inner galaxy.

Figure 2. Comparison of the total calculated γ-ray flux distribution with the SAS-2 longitude data. Contributions from increased secondary electron production and enhanced radiation fields in the inner galaxy are included.

FIGURE 1

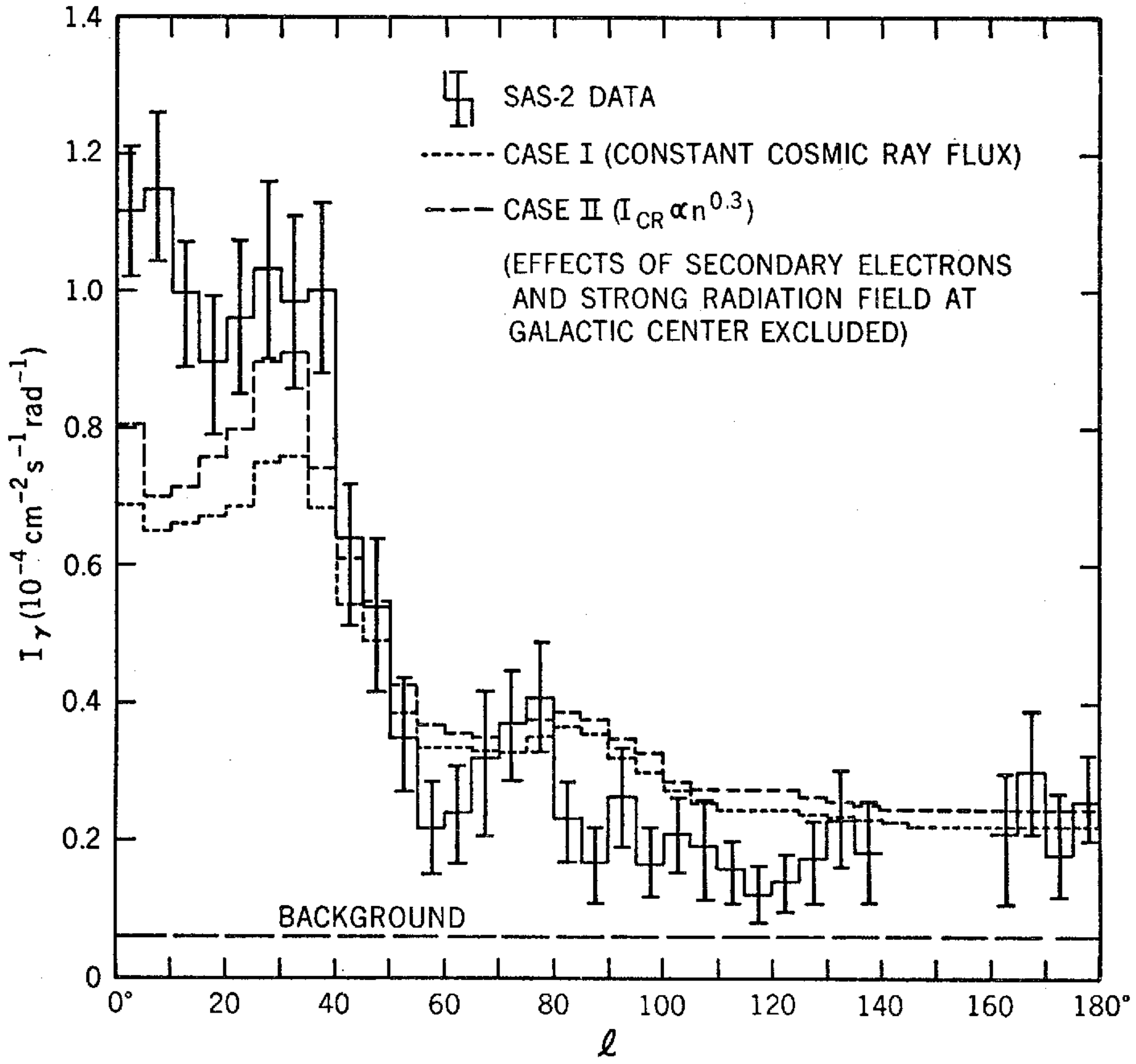
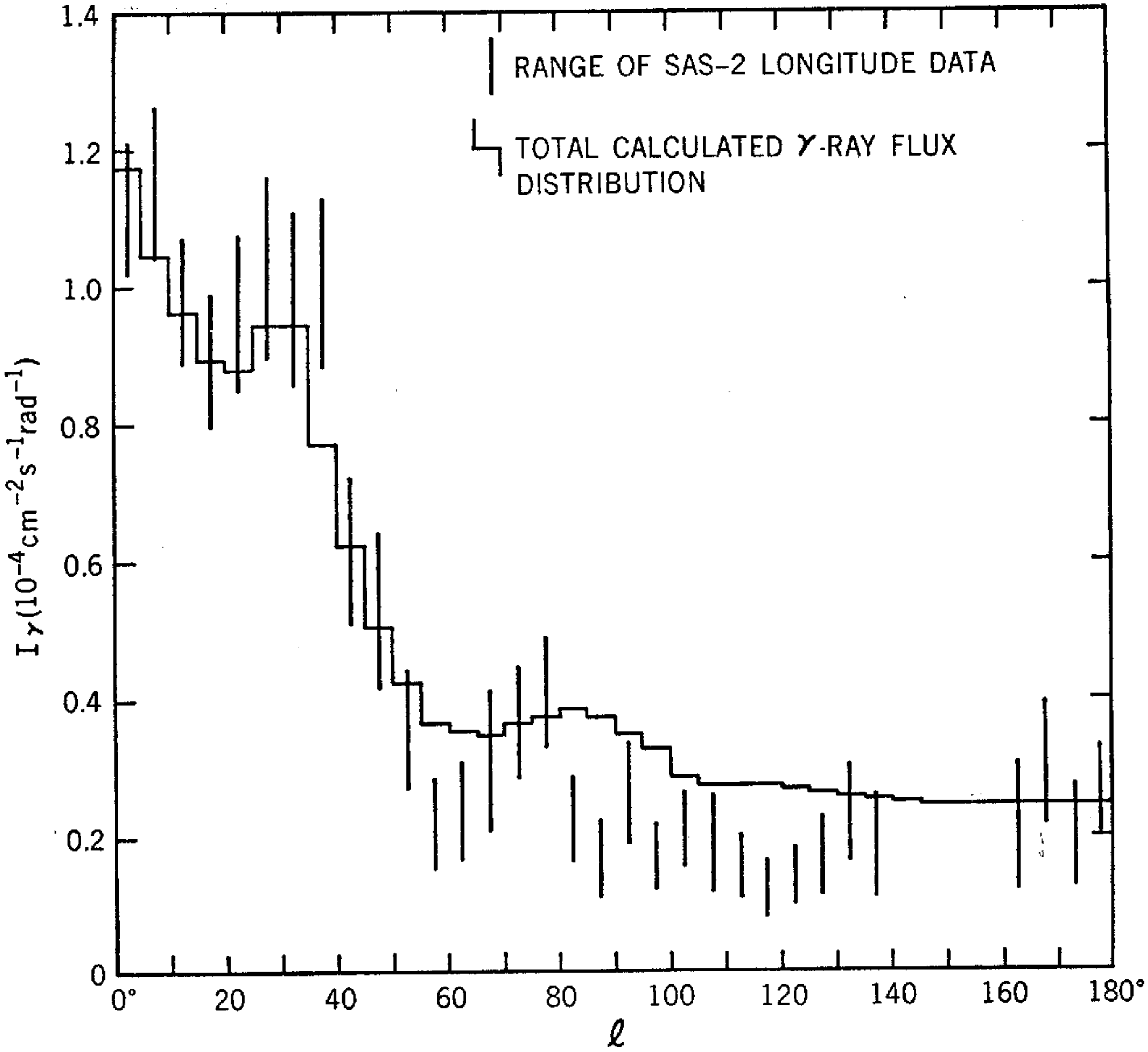

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
$I_\gamma (10^{-4} cm^{-2} s^{-1} rad^{-1})$
0°
20
40
60
80
100
120
140
160
180°
ℓ
SAS-2 DATA
CASE I (CONSTANT COSMIC RAY FLUX)
CASE II ($I_{CR} \propto n^{0.3}$)
(EFFECTS OF SECONDARY ELECTRONS AND STRONG RADIATION FIELD AT GALACTIC CENTER EXCLUDED)
BACKGROUND

FIGURE 2


RANGE OF SAS-2 LONGITUDE DATA
TOTAL CALCULATED γ-RAY FLUX DISTRIBUTION
$I_\gamma (10^{-4} cm^{-2} s^{-1} rad^{-1})$
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0°
20
40
60
80
100
120
140
160
180°
ℓ

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