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A Model of the Diffuse Galactic Gamma Ray Emission

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ABSTRACT

Our galaxy has been observed to be a source of high energy gamma rays as shown by the two successful satellite experiments, SAS-2 and COS-B. It is generally understood that these diffuse gamma rays result from interactions between energetic cosmic rays and interstellar gas. This work makes use of the most recent data on the distribution of atomic and molecular hydrogen in the galaxy along with new estimates of gamma ray production functions to model the diffuse galactic gamma ray emission. The model allows various spatial distributions for cosmic rays in the galaxy including non-axisymmetric ones. In the light of the expected data from EGRET, an improved model of cosmic ray-matter-gamma ray interaction will provide new insights into the distribution of cosmic rays and the strength of its coupling to matter.

INTRODUCTION

The surveys carried out by SAS-2 (Hartman et al., 1979) and COS-B (Mayer-Hasselwander et al., 1982) at high energies (>50 MeV) have yielded intensity and distribution of the diffuse gamma-ray emission from the galaxy. The emission, primarily confined to the galactic plane show clear enhancements along tangent directions to the galactic arms as pointed out by Bignami and Fichtel (1974) and Bignami et al.(1975). It is generally accepted that these gamma-rays result primarily from cosmic ray interaction with interstellar gas and photons via pion decay, electron bremsstrahlung and inverse Compton processes (Pollack and Fazio, 1963 and Stecker, 1971). Interstellar gas, primarily consisting of atomic and molecular hydrogen (90% hydrogen and 10% helium), is mapped using 21 cm line emission from the hyperfine transition of neutral hydrogen and 2.6 mm line arising from $J=1 \rightarrow 0$ transition of ^{12}CO. However, the galactic distribution of cosmic rays has been much harder to carry out. Synchrotron emission from cosmic ray electrons interacting with the interstellar magnetic field does not clearly resolve the issue due to inadequate knowledge of the magnetic field itself. In this context, the recent progress in gamma-ray astronomy has provided what maybe the most valuable tool to study galactic cosmic rays at present. This study reports an attempt to set forth a model based on new gas data and improved gamma-ray source functions to calculate the expected high energy gamma-ray emission from the galaxy.

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The galactic containment of cosmic rays is based on the argument that interstellar magnetic fields embedded in the interstellar gas, confine cosmic ray particles to regions within the galaxy. This idea is substantiated by the observation of pressure balance that exists between cosmic rays, interstellar magnetic fields and the kinematic gas pressure (Parker, 1969). As stated by Parker (1976), the cosmic rays, magnetic field and interstellar gas are all coupled to each other so that the propagation and containment of cosmic rays in the galaxy are inseparable from the dynamical theory of the galaxy. The galactic origin of these cosmic rays and their coupling to interstellar gas via the magnetic field is the basis for considering cosmic ray density distribution to be proportional to the local gas density. The strength of the coupling between cosmic rays and matter is unknown at present and is one of the final goals of this investigation. These have been discussed in further detail by others in these proceedings and also in Bertsch et al.(1990).

Numerous attempts to model the galactic diffuse emission seen by SAS-2 and COS-B in the past (see recent review by Bloemen, 1989) can in general be classified into two approaches. The first approach is to fit the observed gamma-ray data with a axisymmetric multi-parameter function containing measured interstellar gas densities and obtain best fits to the data using techniques such as maximum likelihood (e.g., Strong et al.,1988, Melisse and Bloemen, 1990). In all these cases, an axisymmetric cosmic ray distribution is derived from the best fit parameters. This method does not provide an insight into any possible non-axisymmetric nature of cosmic ray distribution. The second approach which is the basis of this work, directly calculates the expected gamma-ray emission from a calculation using interstellar gas data, known particle interaction cross-sections and photon production source function and an input cosmic ray model (Kniffen and Fichtel, 1981; Fichtel and Kniffen, 1984). Further details on interstellar gas data, cosmic ray models and other details regarding our model are described in the sections below.

PRESENT MODEL

The calculation presented here attempts to model the high energy diffuse gamma-ray emission from the galaxy arising from cosmic ray interactions with galactic matter. An important final goal of this investigation is to derive a more detailed picture of the cosmic ray distribution in the galaxy. The galactic diffuse emission can be reasonably calculated without an exact picture (full 3-D picture) of the matter distribution provided the distribution is consistent with measured line-of-sight column densities and if the cosmic ray density is uniform throughout the galaxy. There are many indications of a non-uniform cosmic ray density in the galaxy such as synchrotron emission arising from interaction of cosmic ray electrons with interstellar magnetic fields show enhancements along the galactic plane with the intensity increasing towards the inner galaxy. This indicates higher cosmic ray electron density towards the inner galaxy if we assume a fairly uniform galactic magnetic field. At present, more details on the cosmic ray distribution is non-existent and only detailed modelling of the diffuse gamma-ray emission will provide some insights in the near future. The model being presented here, predicts diffuse gamma ray emission from the galactic plane and allows flexibility to incorporate various cosmic ray density distributions as well as a choice of normalization factor which converts integrated antenna temperatures of carbon monoxide into molecular hydrogen column densities. Comparing model predictions to existing data from SAS-2 and COS-B and in the future from EGRET, should enable us to narrow down to a more realistic galactic cosmic ray distribution

Interstellar gas

Interstellar gas in our galaxy primarily consists of atomic and molecular hydrogen. Most recent estimates indicate the mass of atomic hydrogen in the galaxy to be ~4.8 x 10^9 M_0 and ~3.5 x 10^9 M_0 or more of molecular hydrogen (Kulkarni and Heiles, 1988). The interstellar gas data used in the calculation presented here is a compilation of various galactic surveys by different groups over many years. The program uses atomic hydrogen data (21 cm emission) surveys of Weaver-Williams (1973) (low latitude galactic H1 survey - l=10°-250°; b=-10°-- +10°), Kerr et al. (1986) (southern H1 survey, l=240°-350°; b=-10°-- +10°) and Burton et al. (1983,1985) (full longitude range and varying latitude range). The latitude range covered by this data set is b=±10°. The molecular hydrogen data (CO) was provided by the Center for Astrophysics in Cambridge from a compilation of fifteen different datasets (Dame et al., 1987). The individual surveys were spread over different latitudes, ranging from b=-25° to +25° with most of them covering ±5° off the galactic plane.

Cosmic Ray models

The axisymmetric cosmic ray distribution derived by Bloemen et al.(1986) by fitting the COS-B gamma ray data indicated an exponential form. Other non-axisymmetric models such as that of Fichtel and Kniffen (1984) assume correlation between matter density and cosmic ray density distributions. The cosmic ray distributions that have been examined in this work include uniform and radially asymmetric distributions. In the non-axisymmetric case, the cosmic ray density distribution is assumed to be directly proportional to the local interstellar gas density. It is assumed that the spectral shape of the cosmic ray spectrum does not change as a function of location within the galaxy.

Gamma-ray production from cosmic-ray interaction with matter

The major processes involved in the production of gamma rays are pion decay into electron-positron pairs, electron bremsstrahlung and inverse Compton interaction. Details on the gamma ray production functions for these mechanisms that are used in this calculation, are discussed in an earlier paper in these proceedings and will not be dealt with here. Contribution to the diffuse gamma ray emission from the inverse Compton process is not included in this preliminary calculation and will be included in a later more complete model.

Description

The model used here directly calculates the gamma ray emission arising from cosmic-ray-gas interactions within the galaxy. The distribution of gas assumed to be mostly in the form of atomic and molecular hydrogen is determined from data taken by various groups as discussed in an earlier section. The galactic plane is divided up from 3.5 kpc to 10.5 kpc into concentric rings 1kpc wide and from 10.5 kpc to 20 kpc into 2 kpc wide rings. The galactic rotation curve of Burton and Gordon (1978) is used to determine the linear velocities corresponding to each concentric ring. Corrections have been made to this rotation curve by Kulkarni (1982) and Fich et al.,(1989), but they are significant only in the outer galaxy (R>10 kpc). Using the local angular velocity which corresponds to the velocity of our frame of reference, one can write down the line of sight component of the linear velocity corresponding to a given galactocentric radius as

$$v(l,R) = R_0 (\Omega(R) - \Omega(R_0) \sin (l) , \qquad \text{where } \Omega(R_0)=25 \text{ s}^{-1} \qquad (1)$$

The location of the Sun (R_0) is taken to be 10kpc. The choice of 8.5 kpc as decided by the 1985 IAU General Assembly, Commission 33 in New Delhi can be easily incorporated into the model when necessary. Kerr and Lynden-Bell (1986) have concluded that kinematic distances within the solar circle derived from a rotation curve and line-of-sight velocities, scale directly with R_0. The gas densities will scale inversely with R_0 ie., a factor of 1.18 (0.85^{-1}) larger while the X-factor used to convert column density of CO into $N(H_2)$ is unaffected (Bronfman et al.,1988). We have decided to use the larger value as the reference value to facilitate comparison with existing results. The integrated intensity of line emission over a velocity range corresponding to a galactocentric ring and a given line-of-sight is proportional to the column density of matter in the intersecting regions of the ring and is given by

$$W = \int_{v(l,i)}^{v(l,i+1)} T_s\, \tau(v)\, dv \qquad \text{where } \tau(v) = -\ln\left(1 - \frac{T_b(v)}{T_s}\right), \qquad \text{where } T_s = 125\text{ K} \qquad (2)$$

T_b is the brightness temperature. The normalization factor $X = N(H_2)/W_{CO}$ used to convert integrated CO intensity to molecular hydrogen density has been a constant source of uncertainty in the calculation of the diffuse gamma ray emission. Various authors have used different values of X but it is generally accepted to fall within 1-3 x 10^{20} mol cm^{-2} (K km s^{-1} $)^{-1}$ (Strong et al.,1988). We have adopted X=2.3 x 10^{20} mol cm^{-2} (K km s^{-1} $)^{-1}$ in determining molecular hydrogen densities. Fitting the model to gamma ray data from COS-B, SAS-2 and in the future with EGRET, will clearly allow us to narrow down the present estimates even further.

The total gamma-ray intensity from the interaction of cosmic rays with galactic matter (excluding inverse Compton) can be written as,

$$j(E_\gamma,l,b) = \frac{1}{4\pi}\int dr\left[q_\gamma^e(E,r{=}0)\times c_e(r,l,b) + q_\gamma^n(E,r{=}0)\times c_n(r,l,b)\right] \rho\,(r,l,b)\, \frac{\text{ph}}{\text{cm}^2\text{ s sr GeV}} \qquad (3)$$

where $\rho(r,l,b)$ is the gas density enhancement factor over local solar value and $c_e(r,l,b)$, $c_n(r,l,b)$ are the corresponding cosmic ray enhancement factors over the average solar system density for electrons and nucleons (Fichtel and Trombka, 1981) We have assumed that the cosmic ray spectral shape does not vary within the galaxy as a whole.

The total hydrogen gas density (atomic + 2 x molecular) in the solar neighborhood was obtained by the Copernicus satellite using UV absorption line measurements. Bohlin et al.(1978) determined the total density to be 1.15 atoms/cm^3. Using the recently determined molecular hydrogen density of 0.10 molecules/cm^3 in the 1 kpc region around the sun (Dame et al. ,1987), the local atomic hydrogen density implied is 0.95 atoms/cm^3. However the atomic hydrogen radio data used in this calculation, yields the local density to be ~0.5 H atm/cm^3 within 500 pc of the sun. The recent calculation carried out by Melisse and Bloemen (1990) also uses n(H1) =0.5 H atm/cm^3 and n(H2) = 0.5(X/2.5 x 10^{20}). We have replaced n(H2) with our estimates of 0.2 Hatm/cm^3 (Dame et al.,1987). This makes the total gas density in the solar neighborhood to be ~0.7 H atm/cm^3. In our model, all cosmic ray distributions are normalized to unity in the solar neighborhood.

We have not included contributions from inverse Compton interactions between cosmic ray electrons and ambient photons (infrared, optical and universal blackbody radiation). This is estimated to contribute less than 10% of the total diffuse gamma radiation in the galactic plane. Since cosmic rays are distributed over larger distances (scale height ~700 kpc) than matter, normal to the plane of the galaxy, the inverse Compton component is expected to be more significant at higher latitudes leading to a broader gamma ray distribution in galactic latitudes.

<u>The Near-Far problem</u>

The galactic rotation curve along with Doppler shifts in emission lines permits us to determine gas density in regions on a galactocentric ring intersected by a given line-of-sight. In the inner galaxy, this leads to two regions, the 'near' and 'far' points where the line-of sight velocity components are equal. In the outer galaxy the distance is uniquely determined. For a complete model of galactic matter-cosmic ray-gamma-ray interaction which will result in an increased knowledge of the spatial distribution of cosmic rays, it is essential to resolve this distance ambiguity in gas distribution in the inner galaxy. I shall describe below an approach that has been considered though limitations with existing data sets has prevented its successful implementation at present.

It is generally accepted that molecular hydrogen in our galaxy mostly exists in the form of dense molecular clouds and that they lie along galactic spiral arms. Dame et al. (1986) and Bronfman (private communication) have reported cloud listings in the first and fourth quadrants with masses above 10^4 solar mass. The clouds in the first quadrant clearly mark out some of the galactic arms. These features are less evident in the fourth quadrant. The distances to these clouds have been determined using various techniques and using related observations of HII regions and OB-star associations (ref Dame et al.,1987). An approach to resolve the 'near-far' problem was to use the new survey by the Center for Astrophysics (Dame et al.,1986) of the galactic plane in CO and examine the contribution of the individual molecular clouds to the total emission. If most of the CO emission can be located in clouds whose distances are known, the 'near' and 'far' regions of an inner galaxy ring can be weighted according to the ratio of the cloud masses at the two locations. In the first quadrant, Dame et al.(1986) account for 18% of the molecular mass in the form of unidentified clouds with known distances. Solomon et al.(1989) have published a much larger cloud listing for the first quadrants and claims to be able to account for ~40% of the mass in the form of clouds. Concerns arise regarding mass determination of clouds using the virial theorem since it provides only upper limits and on the completeness of the cloud sample. They have also not provided similar cloud listing for the fourth quadrant. Further studies needs to be carried out on cloud identification particularly with regards to smaller and more distant ones in order to substantiate claims regarding their role in the total observed emission. Thus existing data on molecular clouds in the inner galaxy does not provide a way to resolve the distance ambiguity problem.

Significance of this model

This model carries out a direct calculation of the diffuse gamma ray emission using the best available data on interstellar gas along with refined gamma-ray source functions for electron bremsstrahlung and pair-production. It permits a choice of possible cosmic ray density distributions of nuclei and electrons independently. The model initially sets out to distribute the interstellar gas over concentric rings, 1 kpc wide. The choice of radial bins allows examination of the galactic morphology such as the 5-kpc 'galactic ring/ spiral arms', within computational and observational limits. The model allows choice of energy ranges from 10 MeV to 30 GeV consistent with EGRET capabilities. The problem of distance ambiguity in the inner galaxy can be examined by allowing different values of near-far distribution ratios that are consistent with existing information on galactic arm structure derived from HII, OB star associations, etc.

RESULTS

In this preliminary study, the predicted gamma-ray emission agrees reasonably well with the observations of SAS-2 and COS-B on a general level. Highlighting some of the differences between the SAS-2 and COS-B results (Fig.1), the model predicts a greater flux in the fourth quadrant compared with COS-B data while SAS-2 results which show sharper profiles than COS-B, indicate closer agreement. Discrepencies in the model results could arise from various factors such as the choice of an inadequate cosmic ray distribution, inappropriate molecular hydrogen normalization factor and due to the absence of contribution from inverse Compton process. The emission from the inner galaxy (l=-90° to +90°) region is dominated by contribution from molecular gas. This implies that, the model is sensitive in the inner galaxy to the molecular hydrogen normalization. On the other hand, emission from the outer galaxy where there is no distance ambiguity problem or uncertain normalization factors, is mostly determined by the atomic hydrogen component. Thus any new information on the outer galaxy cosmic ray distribution will provide an avenue to tie down the molecular hydrogen normalization factor. It is also possible that the amount of molecular hydrogen that is not seen in CO surveys is not negligible, reducing the intensity predicted by the model. From an observational point of view, existing results have been provided by limited angular resolution instruments giving rise to the possible inclusion of a few unresolved source in the measured emission. With the upcoming launch of EGRET on GRO, this issue may be further resolved.

The small contribution to the measured galactic plane emission from the isotropic diffuse emission is determined from the SAS-2 results (Fichtel et al.,1978; Thompson and Fichtel.,1982) to be ~4 x 10^{-6} ph/cm^2-s-rad. Contrary to SAS-2, the COS-B experiment spent many years in an eccentric orbit which can introduce significant difficulties in estimating contribution from instrumental background alone. Only the combined instrument + isotropic background contributions have been reported (Mayer Hasselwander et al.,1982). The reported instrumental background is ~5 times the isotropic flux reported by the SAS-2 team. This could partly explain the difference in the flux estimates reported by the two groups. Estimates of the isotropic emission for SAS-2 and COS-B (taken to be ~8x10^{-6} ph/cm^2-s-rad) are included in the final figures. I shall now discuss the salient features of the predicted longitudinal gamma-ray distribution resulting from this preliminary model. The results are presented as longitude plots of gamma-ray intensity (ph/cm^2-s-rad) where the data has been averaged over the range of +10° to -10° in galactic latitude.

The two cosmic ray distributions being studied here include the simple case of a constant cosmic ray density (equal to the local density) and cosmic ray density proportional to the gas density. The case of a constant cosmic ray density has clearly been shown to be inadequate since it significantly underestimates the gamma ray emission from the inner galaxy inconsistent with observational results from SAS-2 and COS-B (Fig.2). A more realistic model of the cosmic ray distribution would be the case of cosmic rays correlated with interstellar gas. Assuming that cosmic ray density enhancement is equal to gas density enhancements from local value (near solar system), the calculation yields a much better fit to the observed data (Fig.3a,3b). The most interesting aspects of this calculation are seen in the prominent features of the longitude plot of gamma-ray intensity along the galactic plane. The more intense emission arising from large concentrations of gas and cosmic rays in the galactic spiral arms clearly seen in the data, are reproduced by this calculation. These include the tangent point to the 4-kpc arm feature at ~24° and ~342°, the edge of the Scutum and Norma arm at ~36° and ~330° respectively and enhanced emission at ~315° and ~285° from the Crux and Carina arms. The features at ~82° and ~267° maybe due to the local arm. Unfortunately, very strong emission from the point source in Vela, overwhelms contribution from diffuse gamma ray emission around l=267° from the Local arm. The characteristic inter-arm low density region around ~60° is also clearly well reproduced by our model. The tangent to the Sagittarius arm at ~55° is not very dominant. This may not be surprising as seen from CO studies of Dame et al.,(1986) which identified the largest molecular clouds in the first quadrant. The arm itself has been clearly traced by molecular clouds but show only a few large clouds along the line-of-sight tangent to Sagittarius. The region (l~210°-260°) is low in interstellar gas and this is reflected in the lower prediction from the model as compared to SAS-2 results. The model significantly underestimates in this region and may reflect some inadequacies in its preliminary formulation. Modifications to the model in future should make it more complete and it is expected that many of the present inconsistencies will be resolved.

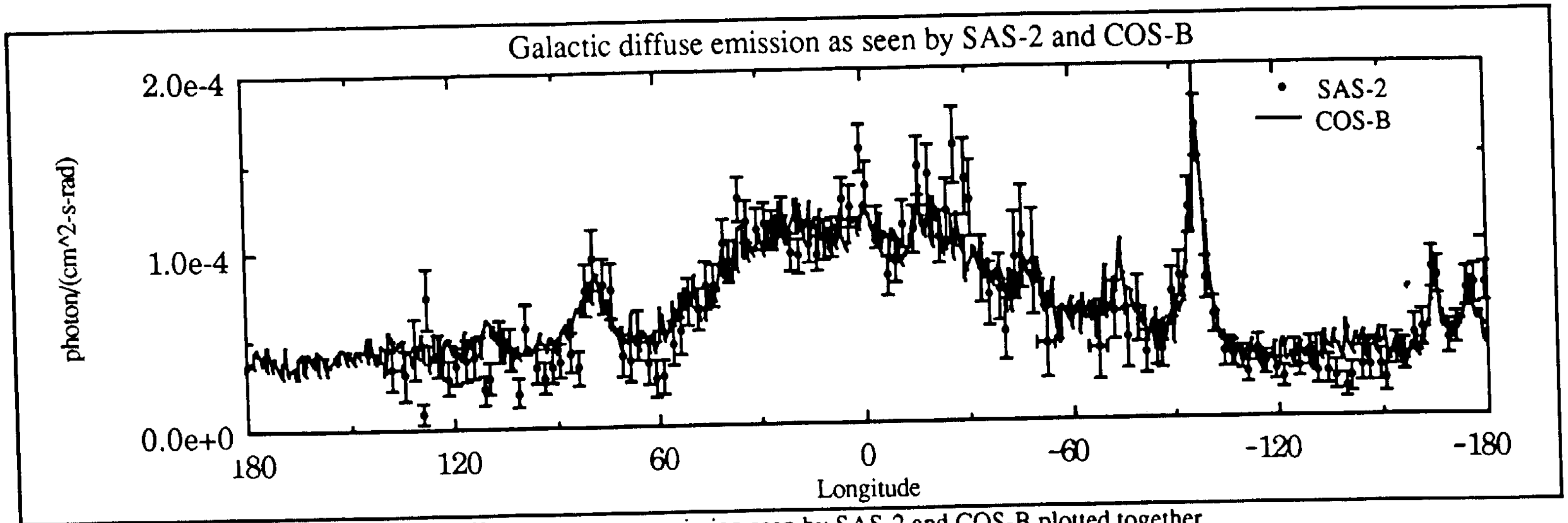

Fig.1: Diffuse gamma-ray emission seen by SAS-2 and COS-B plotted together (100MeV<E<5GeV). Error bars on COS-B data are left out for plot clarity.

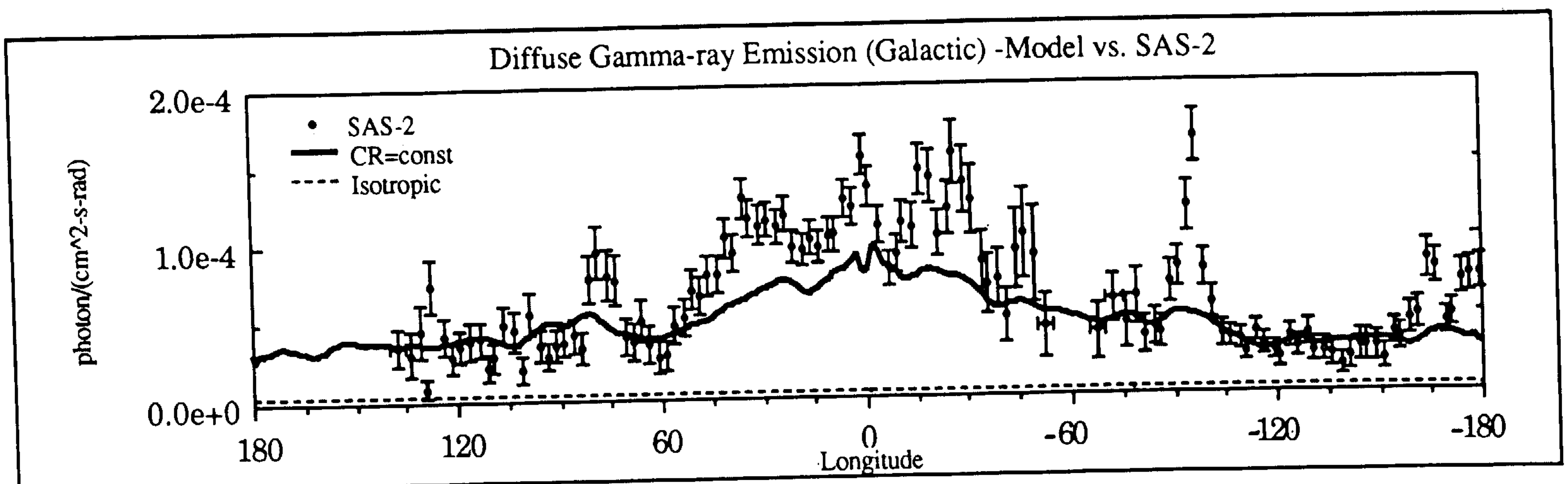

Fig. 2: Results from our model (100MeV<E<5GeV) for the case of a uniform cosmic ray density (local value) along with SAS-2 data (Hartman et al.,1979). The model significantly underestimates the inner galaxy contribution.

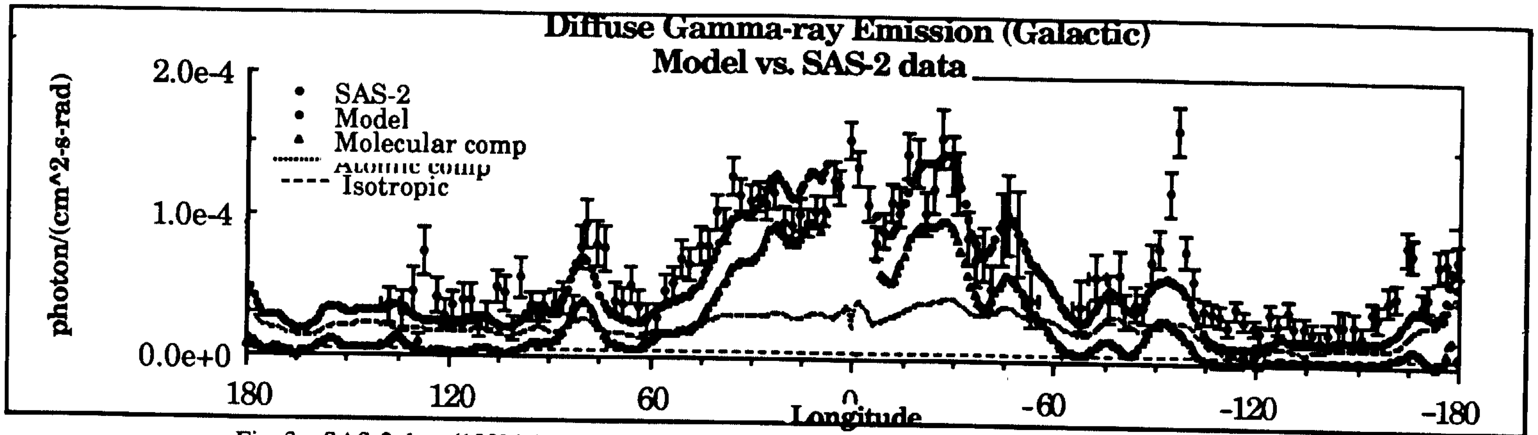

Fig. 3a: SAS-2 data (100MeV<E<5GeV) (Hartman et al.,1979) plotted alongside our model. Cosmic ray density is assumed proportional to local gas density. Contribution from the individual gas components are also shown.

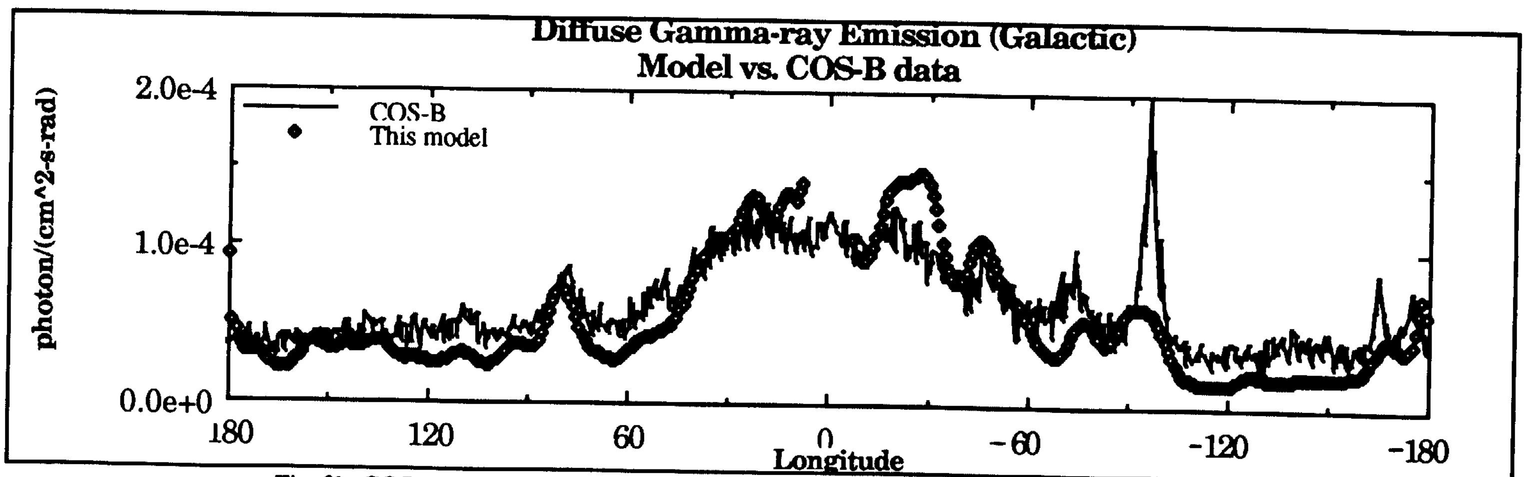

Fig. 3b: COS-B data (Mayer Hasselwander et al., 1982) (100MeV<E<5GeV) plotted alongside our model. Cosmic ray density is assumed to be proportional to local gas density.

FUTURE WORK

The inverse Compton contribution even though small, needs to be included into the present model. The inner galaxy and regions away from the galactic plane are the most sensitive regions with regards to this new component. Various cosmic ray distributions as well as the molecular hydrogen normalization factor X, will be examined to best fit the existing data from SAS-2 and COS-B. New approaches towards resolving the 'near'-'far' problem will be considered. In future, with the launch of GRO, EGRET should provide exciting high quality gamma ray data, leading the way for a significant improvement in our understanding of the galactic cosmic ray distribution and their coupling to interstellar gas.

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DISCUSSION

Gottfried Kanbach:

How do you propose to treat the question of the uncertainty in the distance of the sun to the galactic center, which sets the scale for the model?

P. Sreekumar:

The new galactic constants adopted by 1985 IAU meeting at New Delhi gives the distance to be 8.5 kpc instead of the 10 kpc I have used here. Interstellar gas column densities remain unaffected and will not affect a constant cosmic ray density model. However, the volume density in the inner galaxy increases by a factor of 1.18. This will slightly change the cosmic ray proportional to matter model. The results from the model will be examined for the two cases and it is not expected to be very different (ref. Kerr and Lynden-Bell, 1986).

Floyd Stecker:

One major reason that your flux prediction is low may be that the value of X you used was 2.3, whereas there are arguments that a value close to 3 may be preferred.

P. Sreekumar:

The lower flux predicted was due to a normalization problem associated with the local gas density estimate. Also the choice of X value only affects flux from the inner galaxy where most of the molecular hydrogen is located and does not affect the outer galaxy values. The current best estimate of the X value from gamma-ray astronomy (Strong et al., 1988) is 2.3 or lower. The issue may be further resolved with data from EGRET.

Wim Hermsen:

Melisse and Bloemen compared the COS-B gamma ray survey of the Milky Way with a model in which the cosmic-ray density distribution in the Galaxy is correlated with that of the interstellar gas density on scales of typically 100 pc. Such a model was found to fit the gamma-ray data significantly worse than a model in which the cosmic-ray distribution is relatively uniform, being a function of Galactocentric radius only. This is not caused by small-scale discrepancies, but due to the small scale height of the coupling model.

P. Sreekumar:

It is generally understood that the scale height of cosmic ray-gas coupling is in the range of a few kpc rather than a ~100 pc. As stated by Melisse and Bloeman (1990), their conclusions may not be valid for a larger scale height.

Andy Strong:

The most recent COS-B analysis of the whole galaxy in terms of H1, CO modelling indicated that the molecular component has a steeper spectrum than the atomic. It will be very interesting to see if GRO confirms this. It is therefore important to allow for this possibility in the modelling and not to assume equal spectra.

P. Sreekumar:

Your suggestion will be considered seriously as the model is further refined.