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OBSERVATIONS OF DIFFUSE GALACTIC GAMMA RAYS *

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ABSTRACT

Observations of 35 MeV to several GeV diffuse gamma radiation from the galaxy are available from the SAS-2 and COS-B instruments. This paper gives a brief review of the experimental problem, a discussion of the high-latitude (local) galactic component, and a study of the more distant low-latitude emission from the galactic plane. Finally, the emerging observations in other energy ranges are mentioned.

INTRODUCTION

This paper is a review of the observations of galactic diffuse gamma radiation. Diffuse γ-ray observations in general are of interest because they bear upon three fields of astrophysics: galactic structure, cosmic rays, and cosmology. The cosmological implications are the subject of another review, so I will be concentrating on the connections with galactic structure and cosmic rays.

The bulk of the diffuse galactic gamma radiation which we observe is created in the collisions of cosmic rays with interstellar matter. 1/ Galactic structure is revealed in that the large-scale picture of the plane in the gamma radiation shows features similar to those seen in the distribution of interstellar matter. Cosmic-ray gradients and concentrations, localized and broad scale, are becoming discernible--linked, of course, to progress in estimates of the interstellar matter densities.

Observations of the diffuse galactic emission are not easily made: One requires very low background; and in studying the galactic plane high angular resolution is needed to distinguish the contribution of point sources from truly diffuse emission. Further, the flux of particles is low, $\sim 10^{-5}$ that of cosmic rays. To date, the main experimental results have been obtained with spacecraft in the energy region from 35 MeV to a few GeV. For these reasons, this paper will mainly be a discussion of SAS-2 and COS-B data.

1/ But see also Hayakawa, these proceedings.

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EXPERIMENTAL TECHNIQUE

Gamma rays pass freely through a few gm/cm^2 of matter, leaving no track. However, they may interact catastrophically in the field of a heavy nucleus, converting to an electron-positron pair. In fact, this process is the dominant energy-loss mechanism at all energies above 50 MeV.[1] The pair retains information on the direction and energy of the incident γ-ray, and also provides a unique spatial signature which allows the event to be clearly distinguished from instrumental background. This is seen in Fig. 1, which shows the SAS-2[2] and COS-B[3] instruments.

The detectors consist of a series of thin plates of high Z material in which γ-rays have a high probability of converting to an electron positron pair. Interleaving the plates are x-y digital spark modules, which record the position of the ionized gas left along the tracks of the electron and the positron. The energy of the particles, and thus the γ-ray energy, can be inferred from the rate at which they scatter in traversing the plates (SAS-2) or by stopping them in a thick scintillator (COS-B). The direction of the γ-ray is the mean of the initial directions of the pair.

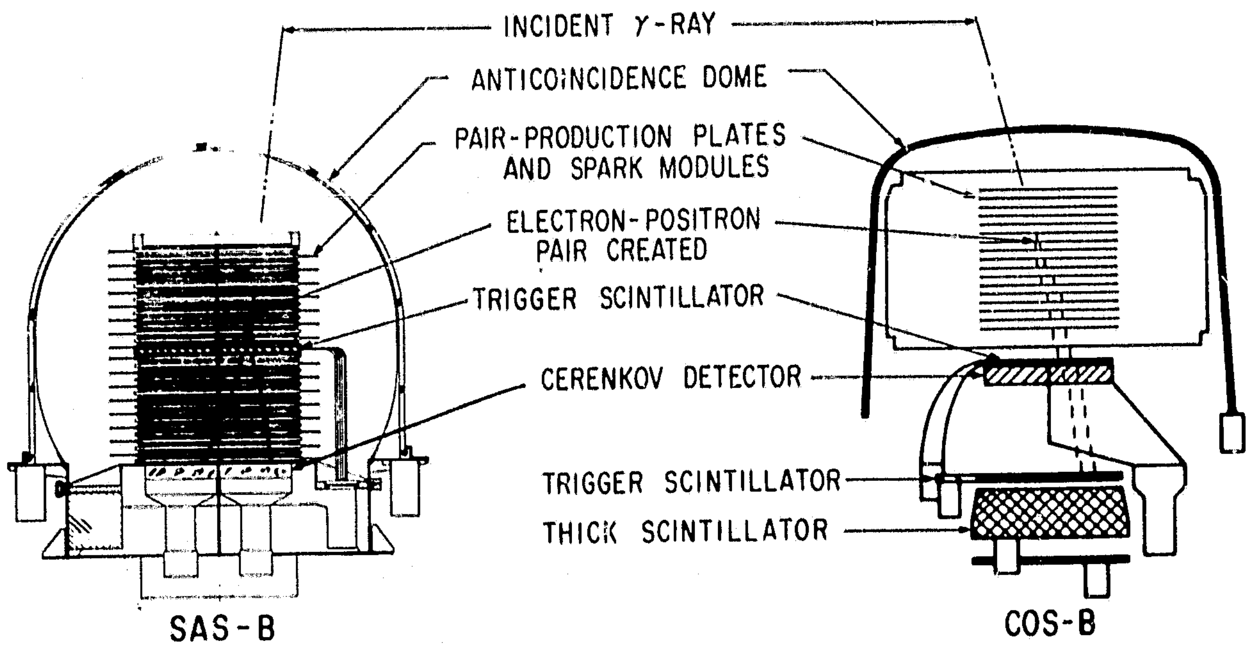

Fig. 1: Gamma-Ray Instruments (50 MeV to several GeV)

The detector triggers when a downward moving particle is noted below the spark chambers and no signal is seen in the anticoincidence dome.

The present generation of detectors achieves angular resolution of a few degrees for each photon (decreasing with energy). The accuracy in locating individual localized γ-ray emission features is limited by the number of photons detectable in reasonable exposure times to values of several tenths of a degree.

The OSO-3 experiment[4,5] was the first to detect the galactic plane, but at this point in time the SAS-2 and COS-B data constitute nearly our entire information base on gamma-ray emission from the galaxy. These two data sets have complementary aspects: COS-B, having a wider energy range and greater exposure time than SAS-2, but also a significant instrumental background, has studied localized emission features in the galactic plane with great success. SAS-2, having negligible background and broader coverage of the celestial sphere, provides the best data for study of the diffuse emission at high latitudes.[6]

GALACTIC GAMMA RAY PRODUCTION

The processes[7,8] that contribute to the diffuse galactic emission at these energies are three, illustrated in Fig. 2: 1) Collisions of GeV cosmic ray nucleons with interstellar matter producing π^0 mesons, which decay to γ-ray photons; 2) Electron bremsstrahlung: radiative interactions of electrons in the nuclear coulomb field; and 3) Compton interactions: Coulomb collisions of electrons >∿10 GeV with ambient photons - principally 3° background radiation galactic infrared radiation, and starlight.

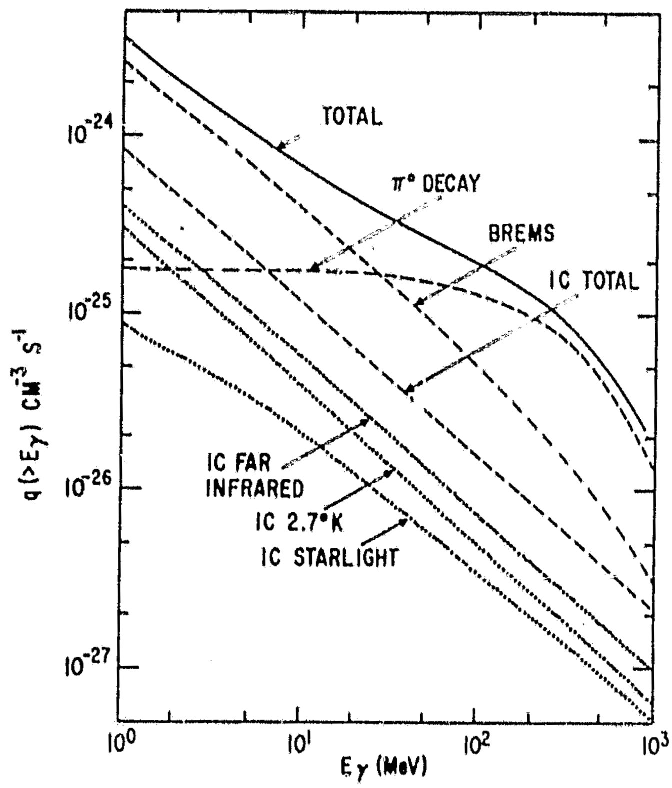

Fig. 2: Local integral γ-ray emissivity for n_H = 1 atom/cm^3 from Worrall (1977) and Stecker (1970)

The π^0 and bremsstrahlung processes dominate at all energies. The key feature of these two mechanisms which has been exploited in observing the diffuse emission is their proportionality to the density of the interstellar medium. The local interstellar medium is believed to consist predominantly of neutral hydrogen, molecular hydrogen being the next most abundant component.[9] If the γ-ray emission which we see is diffuse in origin, then it ought to show a strong correlation with the neutral hydrogen observations[10,11] under the assumption that the cosmic rays are uniformly distributed.

HIGH LATITUDE OBSERVATIONS

First let us consider a region of the galaxy where we can be confident that that assumption is true: the region within 500 pc of the sun. Of course, we have no information at all on the distance at which individual γ-rays originated, but we can use the well-measured properties of the matter distribution. The scale height of neutral hydrogen is 130 pc locally. Therefore, if we confine our observations to galactic latitudes more than 12° from the plane, the diffuse matter, and thus the majority of the predicted diffuse emission, will have been generated within 500 pc of the sun. 500 pc is 3% of the galactic radius, and the order of the width of a spiral arm.

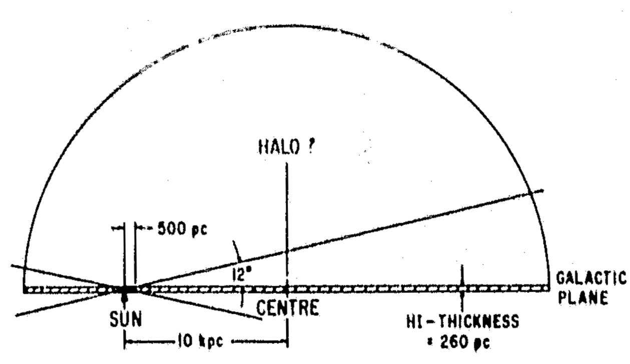

Fig. 3: Geometry of high-latitude γ-ray observations.

Our dataset is rather sparse: even with the 28-week exposure of SAS-2, only about 4000 photons were observed from latitudes outside 12°. This means that we can consider only broad-scale features of the high-latitude γ-ray distribution.

We may consider the correlation of the high-latitude γ-ray intensity with the neutral hydrogen column density[12] with the objectives of determining (1) if there exists a component of the gamma-ray intensity which is not correlated with the matter disk (i.e. an extragalactic or halo component) and (2) if the observed γ-ray intensity is consistent with observed and inferred properties of the cosmic rays.

The γ-ray intensity for high latitudes is shown plotted as a function of the 21 cm column density in Fig. 4. Here we have selected γ-rays >100 MeV, and we have divided the galaxy into broad regions of longitude (typically 60°) and latitude (10°), averaging and smoothing the 21 cm observations to match the lower resolution of the γ-ray data. We see from the figure that the γ-ray intensity in every region is consistent with a single linear correlation of the form

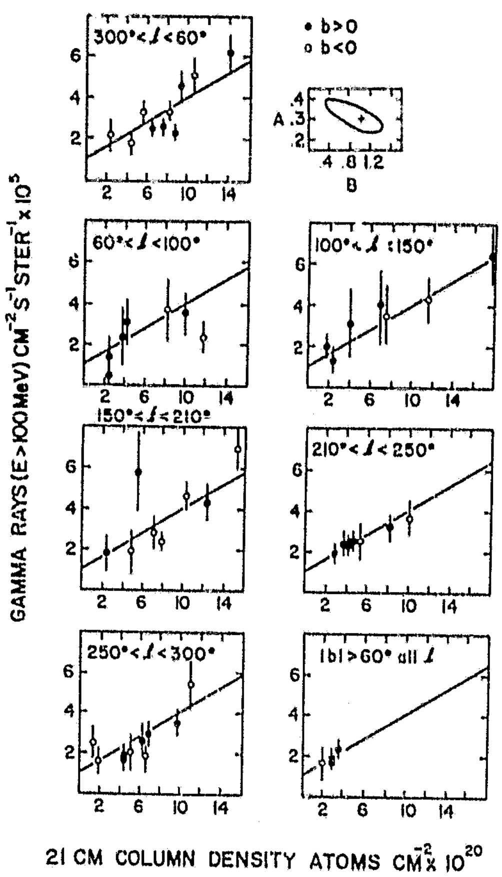

Fig. 4: The correlation between γ-ray intensity and column density of neutral hydrogen at high latitudes (12)

$$I_\gamma = A \cdot N_{HI} + B$$

This relationship also holds in the 35-100 MeV range, with different coefficients reflecting the different spectra of the two components. The slope 'A' gives directly the γ-ray photon production rate per atom of neutral hydrogen, while the intercept 'B' gives the intensity of a component which is uncorrelated with the matter, possibly originating in the galactic halo or outside our galaxy. Assuming power-law spectra, the galactic 'A' component has a spectral index 1.5 ± 0.03 and intensity above 35 MeV of $(6.2 \pm 1.5)\ 10^{-26}\ N_{HI}$, while for the 'B' component these figures are $2.7^{+.4}_{-.3}$ and $5.7\ 10^{-5}$ photons $cm^{-2}s^{-1}\ sr^{-1}$. For >100 MeV γ's the two components are equal at galactic latitudes near 30°, varying somewhat with longitude.

We can calculate the expected disk component using measurements of the cosmic ray proton and electron spectra and the interstellar matter density. The local interstellar densities of both HI and H_2 have been sampled by UV absorption measurements from the Copernicus satellite[13]; the nominal value is 1.15 atoms/cm^3 of hydrogen in all forms. Proton spectra at the Earth have been well measured for some time and the correction for solar modulation at the energies of interest (>2 GeV) is negligible. Interstellar electron spectra, which we require to compute the bremsstrahlung and Compton components, are rather uncertain.

However, the spectrum of Cummings[14], or Daugherty et al.[15] can be used as a starting point. One important result of this calculation[12] is that a higher contribution from electrons, at least 50% more than Cummings (1973) is required to account for the spectral index. Some independent evidence for a higher electron intensity in the energy range around 1 GeV has been given by recent measurements[16] of the 5-80 MHz spectrum of synchrotron emission in the north and south galactic pole directions. When these new data are used with measurements of the high energy electron spectrum at Earth to rederive the interstellar electron spectrum,[17] a much better agreement with the requirements of the high-latitude gamma-ray observations is found. The best currently available estimates of the galactic γ-ray production rates are shown in Table 1.

TABLE 1 Source Functions In The Solar Vicinity

SOURCE MECHANISM	VALUE OF SOURCE FUNCTION ($CM^{-3} S^{-1}$)	
	$10 < E(MeV) < 30$	$E(MeV) > 100$
COSMIC RAY NUCLEON MATTER INTERACTIONS	$(0.7-1.1) \times 10^{-26}$	$(14-22) \times 10^{-26}$
ELECTRON BREMSSTRAHLUNG	$(13-39) \times 10^{-26}$	$(4-12) \times 10^{-26}$
COMPTON SCATTERING (STARLIGHT AND INFRARED)	$(1.2-3.6) \times 10^{-26}$	$(0.4-1.2) \times 10^{-26}$
COMPTON SCATTERING (3°K)	$(1-3) \times 10^{-26}$	$(0.2-0.6) \times 10^{-26}$
SYNCHROTRON RADIATION	$(0.7-2) \times 10^{-30}$	$(0.3-0.4) \times 10^{-30}$
POINT SOURCES	?	?

The residual component of the high latitude gamma radiation is more difficult to interpret. However, we can immediately place some constraints on halo models for its origin by looking for anisotropies. Subtracting the disk component from the total emission in each direction, and comparing the remaining intensity from directions which pass over the galactic center to that from the anticenter directions (with $20° < |b| < 60°$) one finds a ratio of 1.10 ± 0.18.

If there existed an extended uniform cosmic ray halo of cylindrical geometry such as has been suggested[18], the ratio of Compton black-body γ-rays would be about 5. A uniform spherical halo of galactic dimensions gives 2.8. Models have been produced which include electron energy loss and diffusion, and give the predicted ratio as a function of energy and electron diffusion coefficient, assuming free escape into the halo. The values are around 3 to 4.[19]

If we allow the halo component to be 'diluted' by an isotropic component of extragalactic origin, then these figures imply that the halo must contribute less than 20% of the 'B' component (2σ upper limit).

LOW-LATITUDE γ-RAY EMISSION

The γ-ray map of SAS-2[20], which includes some 14,000 photons, and that of COS-B[21] (64,000 photons) are shown in Figs. 5 and 6. The most prominent features in each of these maps are the galactic plane, and the bright localized emission regions which have been discussed in earlier papers.

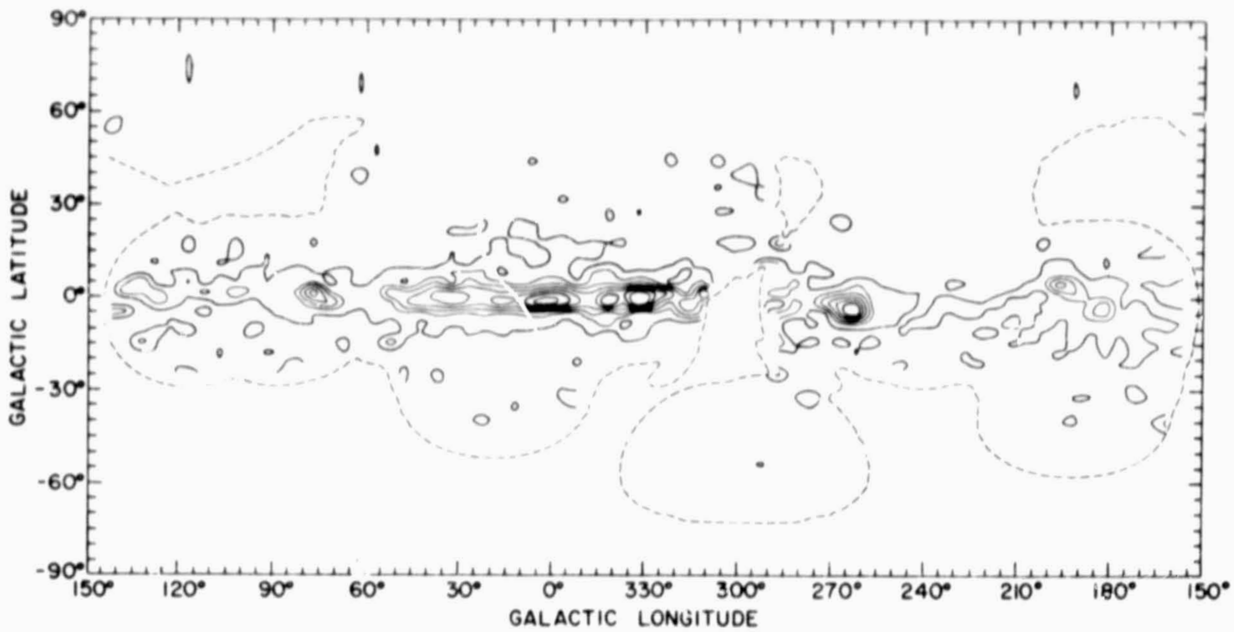

Fig. 5: The SAS-2 map of > 100 MeV γ-rays

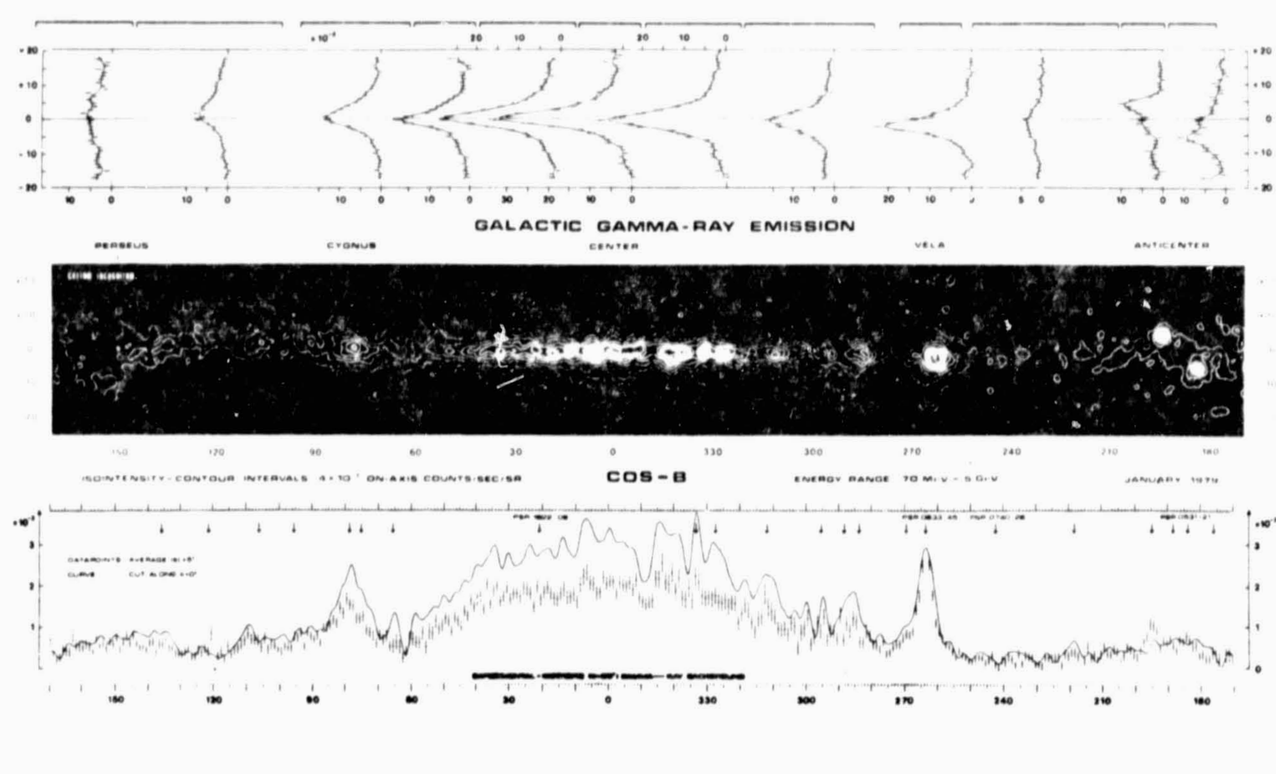

Fig. 6: The COS-B map of > 70 MeV γ-rays[21]

The galactic plane is far more intense in directions toward the center than away from the center, which is to be expected since even γ-rays from the far side of the galaxy have only a small chance of being absorbed in their travel to our instruments. Toward the center, we are seeing emission which was produced, on the average, at the galactic center, 10 Kpc away. Thus in the galactic center latitude profile we would expect a FWHM of about 1.5°, less than our detector resolution.

The observed latitude distributions (Figure 6) towards the center show a narrow component corresponding to these distant regions of the disk, with a broader asymmetric component enhanced in the region $6° < |b| < 20°$. The complementary asymmetry which can be seen at negative latitudes in the anticenter direction (when the Crab and γ195 + 5 are subtracted) suggests that both these broad features are emission from the Gould's belt local cloud cluster. Another feature which can be seen is a small overall tip of the galactic plane relative to $b = 0°$ in the latitude profile near $\ell = 230°$: the "hat-brim effect." This effect has also been seen in HI as well as in the distribution of localized γ sources. 2/

The longitude profiles from the two experiments, as shown in Figure 7, are very similar. Here the COS-B data, shown as open circles, is superimposed on that of SAS-2, and we have chosen the scales seen on the right and left axes to match at the galactic center. There are no statistically significant disagreements at present, although we are anxious to see the COS-B data given in absolute flux units.

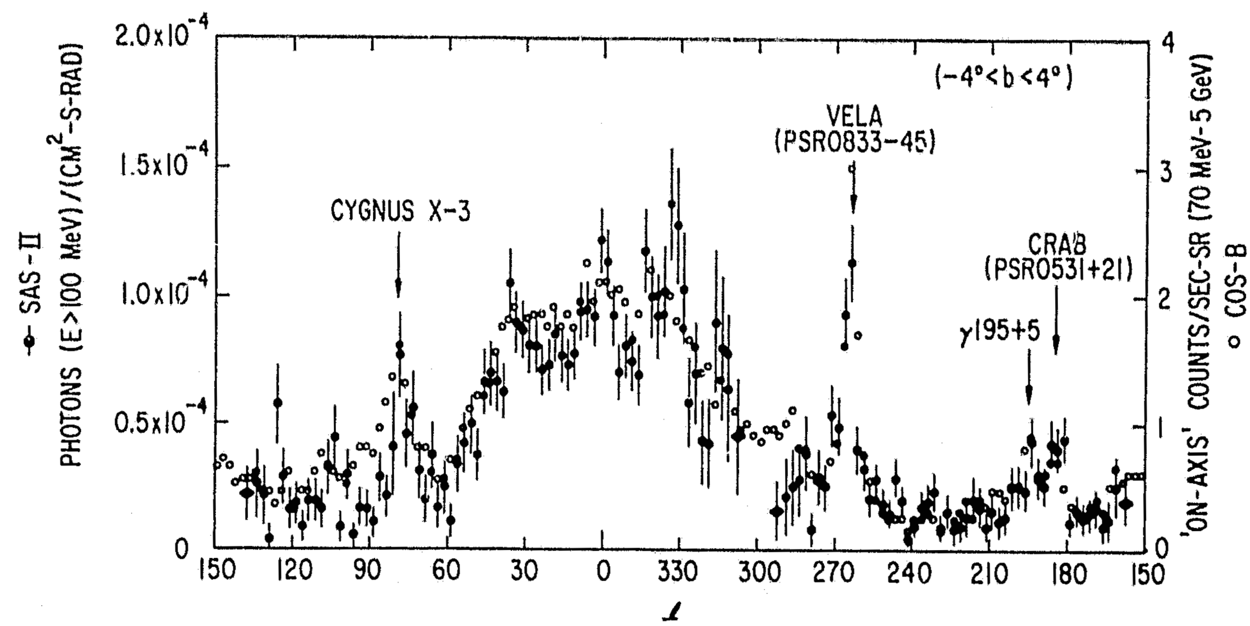

Fig. 7: SAS-2 and COS-B γ-ray intensity along the galactic plane. [22], [21]

2/ See Wills et.al., this volume.

Various interpretations of the longitude profile have been suggested. One feature on which all agree is that the contrast between the intensity from directions toward and away from the center is stronger than the contrast which one finds in the matter distribution. This observation has been variously explained as a correlation of cosmic ray density with spiral arms,[22] the 4 kpc ring,[23] or pulsars and supernova remnants.[24] The data do not distinguish decisively among these and other similar possibilities.

The presence of a peak at the galactic center is an example of the type of observational feature which we may regard as possible, but in need of better observations.

It is quite interesting to extend the analysis of the γ-ray matter correlation to distant regions of the plane, as shown in Figure 8. As I showed for the high latitude emission, the 21 cm column density is used as the abscissa, and the line shown is that which fits the high-latitude data. Quite prominent in this figure are the excess of γ-ray intensity toward the center of the galaxy, and the deficit in regions away from the center. These deviations only appear in the points at the highest column densities, which are right in the plane, and therefore, most distant. A contribution to the enhancement toward the center is undoubtedly due to hydrogen in molecular form, which is known to be more concentrated toward the galactic center than neutral hydrogen. But quantitatively it seems most probable that cosmic ray intensity must also increase toward the galactic center and decrease at radii beyond the sun. This radial gradient of cosmic rays has been used to argue that the cosmic-ray trapping region cannot extend far above the disk of the galaxy.[25] If it did, the strong concentrations would disappear because of the lack of confining magnetic structure above the plane.

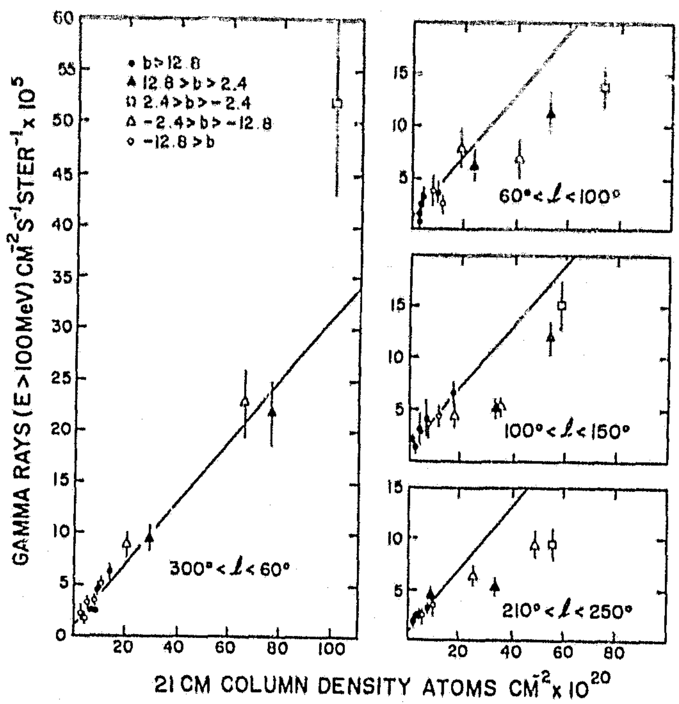

Fig. 8: The correlation between diffuse γ-ray and intensity and neutral hydrogen column density, at all galactic latitudes. (12)

One of the most interesting questions currently being asked is "Can the longitude distribution be explained as predominantly diffuse emission, or is most of it made up of unresolved point sources?" The answer to this question must await instruments of better angular resolution, but several pieces of evidence that bear on it are worth discussing.

The argument for unresolved point sources[26,27,28] is based on the observation by COS-B of a large number (30 at present) of localized emission features which are believed to represent a partial sample of the discrete source emission within 5 kpc of the sun. The portion of the diffuse emission which can be made up depends strongly on assumptions regarding the distribution and luminosity of the sources, estimates ranging beyond 40%.

A difficulty with this debate is the lack of a precise distinction between the definitions of point source and diffuse emission. I have characterized diffuse emission as due to cosmic-ray matter and photon interactions. Between this extreme and γ-ray pulsars, which certainly are point sources, one probably has a whole spectrum of objects such as molecular clouds and cosmic-ray Fermi acceleration sites, which can appear as point-like to current γ-ray instruments, but are spatially extended and involve the diffuse processes.

The arguments in the data for the predominance of diffuse emission are as follows:

(1) At high latitudes, where the point source contribution is negligible, the diffuse γ-ray production rate is similar to that required to produce the majority of the intensity seen from the rest of the plane.[12]

(2) The spectrum of the γ radiation from the plane has been extensively measured[29,30,31] and is shown in Fig. 9. Its shape is the same in all regions of the plane, and like the high-latitude spectrum, it requires a larger electron contribution. I have also shown the high-latitude diffuse galactic spectrum[12] and its associated uncertainty to make graphic the fact that these agree within errors. This is circumstantial evidence for predominantly diffuse origin. By contrast, of the four strongest point sources, two have spectra different than the plane, while the other two are similar.

(3) If one tries to model the longitude distribution using the matter distribution and a constant cosmic-ray density, the attempt is unsuccessful. But by invoking proportionality between cosmic rays and matter on the scale of spiral arms,[22] the distribution is fitted rather well. Similarly, the assumption that cosmic-ray sources are distributed like supernova remnants and molecular hydrogen fits the longitude data.

OBSERVATIONS IN OTHER ENERGY RANGES

Before concluding, it is important to mention progress being made in other regions of the gamma-ray spectrum. The problems of background removal and limited angular resolution are exacerbated below 35 MeV and above several GeV; but even so, significant progress is being made. At the present the observations in the range from .5 MeV to 20 MeV have resolved the plane and its spectrum,[31,32,33] observed the brighter galactic and extragalactic point sources[34] and indicated the spectrum at high latitudes.[35]

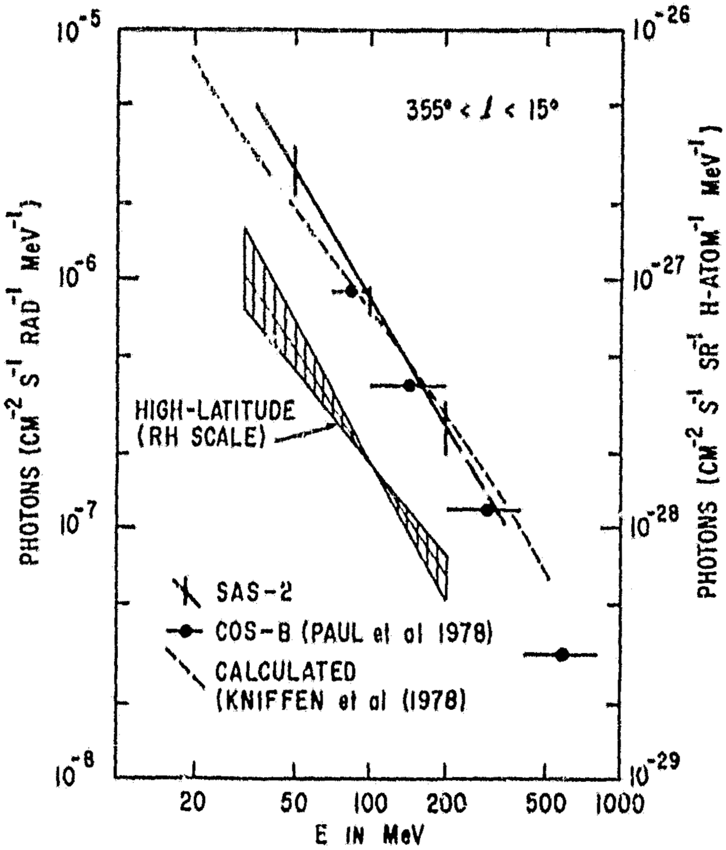

Fig. 9: Galactic γ-ray energy spectrum (12,30)

The techniques include solid-state and crystal spectrometers[33] (.06-5 MeV), double Compton scattering [34,35] (1-20 MeV), and pushing the pair-production technique to lower energies.[31] At much higher energies (10^{11} to 10^{14} eV) atmospheric Cerenkov γ-ray observations have set upper limits on the intensity from some point sources.[36,37,38] However, it appears that some new technique will be needed to make observations of the diffuse component at these very high energies.

CONCLUSION

To summarize, observations of diffuse γ-ray emission from the galaxy have told us that (1) there are more cosmic-ray electrons in the range .1-1 GeV than we used to think; (2) the galactic halo can contribute at most 20% of the emission which is not connected with the galactic matter disk; and (3) there appears to be a radial gradient of cosmic rays in the galaxy.

Prospects for progress in observations of diffuse γ-rays are excellent, especially as the possiblity of a major γ-ray observatory in orbit approaches. Particularly exciting for diffuse galactic astronomy is the prospect of measuring the interstellar electron spectrum at low energies through its bremsstrahlung emission. This observation may impose new constraints on theories of electron acceleration and solar modulation.

REFERENCES

1. B. Rossi, High-Energy Particles, Prentice-Hall, 1952, p. 79.

2. C. E. Fichtel, R. C. Hartman, D. A. Kniffen, D. J. Thompson, G. F. Bignami, H. Ögelman, M. E. Özel, and T. Tümer, Ap. J. 198, 163 (1975).

3. K. Bennett, J. J. Burger, H. Gorisse, H. A. Mayer-Hasselwander, E. Pfefferman, P. G. Shukla, R. Stiglitz, B. N. Swanenburg, B. G. Taylor, and R. D. Wills, Ninth ESLAB Symposium, ESRO SP-106, 323 (1974).

4. W. L. Kraushaar, G. W. Clark, G. P. Garmire, R. Berken, P. Higbie, V. Leong, and J. Thorsos, Ap. J. 177, 341 (1972).

5. G. W. Clark, G. P. Garmire, and W. L. Kraushaar, Ap. J. Lett. 153, L203 (1968).

6. C. E. Fichtel, R. C. Hartman, D. A. Kniffen, D. J. Thompson, H. G. Ögelman, T. Tümer, and M. E. Özel, Tabulated data from the SAS-2 High Energy Gamma-Ray Telescope NASA TM 79650.

7. F. W. Stecker, Astrophys. Space Sci. 6, 377 (1970).

8. D. M. Worrall, Thesis, University of Durham, 1977.

9. W. B. Burton, The Structure and Content of the Galaxy and Galactic Gamma Rays, ed. Fichtel and Stecker, 1976.

10. C. Heiles, Astro. Ap. Suppl. 20, 37 (1975).

11. S. C. Simonson, III, Astron. Astrophys. 46, 261 (1976).

12. C. F. Fichtel, G. A. Simpson, and D. J. Thompson, Ap. J. 222, 833 (1978).

13. R. C. Bohlin, R. D. Savage, and J. F. Drake, Ap. J. 224, 132.

14. A. C. Cummings, Ph.D. Thesis, Caltech, Pasadena, 1973.

15. J. K. Daugherty, R. C. Hartman, and P. A. Schmidt, Ap. J. 198, 493 (1975).

16. H. V. Cane, Ph.D. Thesis, University of Tasmania (1977).

17. W. R. Webber, H. V. Cane, and G. A. Simpson, Ap. J., in press (1979).

18. V. S. Ptuskin and Ya. M. Khazan, Astrafizika, 12 #1, 81, 1976.

19. D. M. Worrall and A. W. Strong, Astron. Astrophys. 75, 229 (1977).

20. D. A. Kniffen, C. E. Fichtel, R. C. Hartman, R. C. Lamb, and D. J. Thompson, Proceedings 12th ESLAB Symposium Frascati, 45, 1977.

21. H. A. Mayer-Hasselwander, K. Bennett, G. F. Bignami, R. Buccheri, N. D'Amico, W. Hermsen, G. Kanbach, F. Lebrun, G. G. Lichti, J. L. Masnou, J. A. Paul, K. Pinkau, L. Scarsi, B. N. Swanenburg, and R. D. Wills, to be published in Proceedings of the 9th Texas Symposium in 'Annals of the New York Academy of Sciences', 1979.

22. G. F. Bignami, C. E. Fichtel, D. A. Kniffen, and D. J. Thompson, Ap. J. 199, 54 (1975).

23. F. W. Stecker, in The Structure and Content of the Galaxy and Galactic Gamma Rays, ed. Fichtel and Stecker.

24. D. Dodds, A. W. Wolfendale and E. C. M. Young, Proc. 15th Int'l Conf. Cosmic Rays, Plovdiv, 1977.

25. F. W. Stecker and F. C. Jones, Ap. J. 217, 843 (1977).

26. H. Ögelman, Nature 221, 753 (1969).

27. J. C. Higdon and R. E. Lingenfelter, Ap. J. 208, L107 (1976).

28. G. F. Bignami, P. Caraveo, and L. Maraschi, Astron. Astrophys. 67, 149 (1978).

29. R. C. Hartman, D. A. Kniffen, D. J. Thompson, C. E. Fichtel, H. B. Ögelman, T. Tümer, and M. E. Özel, Ap. J., in press.

30. J. A. Paul, K. Bennett, G. F. Bignami, R. Buccheri, P. Caraveo, W. Hermsen, G. Kanbach, H. A. Mayer-Hasselwander, L. Scarsi, B. N. Swanenburg, and R. D. Wills, Astron. Astrophys. 63, L31 (1978).

31. D. A. Kniffen, D. A. Bertsch, D. J. Morris, R. A. R. Palmeira, and K. R. Rao, Ap. J. 225, 591 (1978).

32. S. M. White, S. Moon, J. M. Ryan, R. B. Wilson, A. D. Zych, and B. Dayton, Proc. 15th Int'l Conf. Cosmic Rays, Plovdiv, 1, 100, 1977.

33. J. I. Trombka, C. S. Dyer, L. G. Evans, M. J. Beilefeld, S. M. Selzer, and A. E. Metzger, Ap. J. 212, 925 (1977).

34. V. Schonfelder, U. Graser, and J. Daugherty, Ap. J. 217, 306 (1977).

35. F. Graml, MPI - PAE/Extraterr. 151 (thesis), 1977.

36. N. A. Porter and T. C. Weekes, Smithsonian Astrophysical Observatory, Special Report 381, 1978.

37. T. C. Weeks, G. G. Fazio, H. F. Helmken, E. P. O'Mongain, G. H. Ricke, Ap. J. 174, 165 (1972).

38. J. E. Grindlay, H. F. Helmken, R. H. Brown, J. Davis, and L. R. Allen, Ap. J. 201, 82 (1975).