FR8300700

8. European cosmic ray symposium
Roma, Italy 8 - 16 Sep 1982
CEA-CONF--6504

OBSERVATION OF GALACTIC GAMMA RADIATION

J.A. PAUL
Section d'Astrophysique, Centre d'Etudes Nucléaires de Saclay, France

ABSTRACT

A complete and deep survey of the galactic high-energy gamma radiation is now available, thanks to the gamma-ray telescopes on board of the SAS-2 and COS-B spacecrafts. A comparison of the COS-B gamma-ray survey with a fully sampled CO survey together with an H_I survey is used to show that a simple model, in which uniformly distributed cosmic rays interact with the interstellar gas, can account for almost all the gamma-ray emission observed in the first galactic quadrant. At medium galactic latitudes, it is shown that a relationship exists between the gamma radiation and the interstellar absorption derived from galaxy counts. Therefore gamma rays from the local galactic environment can be used as a valuable probe of the content and structure of the local interstellar medium. The large scale features of the local interstellar gas are revealed, in particular wide concentrations of nearby molecular hydrogen. On a smaller scale, the detection of numerous localized gamma-ray sources focuses the attention on some particular phases of clusters of young and massive stars where diffuse processes of gamma-ray emission may also be at work.

I. INTRODUCTION

At the end of the COS-B mission (April 1982), after more than 6 1/2 years of high-energy gamma-ray observation, the understanding of the galactic gamma radiation can take great advantages of the unprecedented details of the gamma-ray Milky Way as mapped by the COS-B experiment. But, in the meantime, the COS-B mission has brought an element of confusion in the conventional picture of the galactic emission, namely the discovery of many discrete sources. These objects contribute to the overall emission but, owing to their unknown physical nature, they should be distinguished from the diffuse gamma radiation which originate from the interaction of energetic cosmic rays with the interstellar matter and radiation fields. However, thanks to the efforts of many astrophysicists, deeply involved in the interpretation of the gamma-ray results, it is now possible in certain cases to disentangle the contribution from diffuse processes in correlating the gamma-ray results with total gas tracers.

It is the purpose of the present paper to give a status report on the knowledge of the diffuse galactic emisison of high-energy gamma rays either on a large scale (§ II) and in the local galactic medium (§ III). Diffuse processes may also be at work in a class of localized sources as discussed in § IV. Non diffuse processes, as e.g. the gamma-ray emision from radio pulsars, are beyond the scope of this paper. A review of such processes can be found in Cesarsky and Paul (1981).

II. LARGE SCALE EMISSION

For obvious statistical reasons, only large scale studies were performed on the gamma-ray data from the pre COS-B era. At this time, it was postulated that the galactic high-energy gamma radiation is purely of diffuse origin. In this context, it is quite easy to derive the cosmic-ray distribution in the galactic disc, provided that its gaseous content is known. Conversely, it is also possible to estimate the total gas distribution in the framework of models where the cosmic-ray distribution is determined on the basis of theoretical arguments. But since the first results of the COS-B mission stressing the role of the gamma-ray sources (Hermsen et al. 1977), it is clear that the basic postulate of a purely diffuse origin of the galactic gamma rays should be ruled out. It is also recognized that the gas content of the galactic disc is far from being well krown, in particular its molecular fraction (see e.g. the discusison in Lequeux 1981).

At present, the COS-B satellite has provided a complete picture of the Milky Way (Mayer-Hasselwander et al. 1982), and a complete CO survey with a large latitude extent has been undertaken in the first galactic quadrant with the Columbia millimeter-wave telescope (Dame and Thaddeus 1982). The widely observed 2.6 mm line emitted by the CO molecule is a tracer of molecular clouds, which are believed to contain a significant fraction of the interstellar gas ; the remaining part, mainly in atomic form, is well depicted by the 21 cm line. Thanks to the completeness of the CO and gamma-ray survey, it is possible to compare in detail the brightness of the 2.6 mm CO and 21 cm H_I lines with the gamma-ray intensity (Lebrun et al. 1983). A way independent of a priori interpretations of the data is to try to reproduce the observed gamma-ray emission with a combination of gas tracers in the form :

$$I_{\gamma_p} = A\tilde{N}(H_I) + B\,\tilde{W}_{CO} + C \qquad (1)$$

where I_{γ_p} is the predicted gamma-ray intensity ; $\tilde{N}(H_I)$ is the atomic hydrogen column density, derived from 21 cm line observation and convolved with the appropriate COS-B point spread function (PSF) ; $\tilde{W}_{CO}$ is the integration of the CO spectra over all velocities, also convolved with the COS-B PSF. The first result of this work, restricted to the high-energy gamma rays ($E \gtrsim 300$ MeV), are summarized in fig. 1 and 2 (Lebrun 1982). The values of the parameters A, B and C were obtained by maximizing the probability of obtaining the observed gamma-ray map given the predicted one. It is apparent that these maximum likelihood estimates of parameters A, B and C are well suited to reproduce the observations either at low galactic latitudes ($|b| \leq 5.5°$) and in the latitude range ($5.5° \leq b \leq 10.5°$) as shown in fig.1. The agreement between the latitude distribution of the observed and predicted gamma-ray emission for various longitude intervals is apparent in fig. 2. It should be stressed that the width of these distributions is much larger than the experiment PSF and that the asymmetries around the plane are also reproduced.

The gamma-ray intensity can be considered as the sum of contributions from : (i) cosmic-ray (both electrons and nuclei) interactions with atomic and molecular hydrogen, (ii) localized sources, (iii) extragalactic emission and instrumental background. Gamma rays can also be produced by the interaction of high-energy cosmic-ray electrons with the ambient photon field, but such a mechanism does not contribute significantly above 300 MeV. Both extragalactic emission and instrumental background are isotropic and could be identified with the term C in relation (1). The fact that a linear relation involving the H_I and H_2 gas tracers is able to account for the observed gamma-ray intensity could be in the simplest way interpreted as follow :

- a strong galactic cosmic-ray gradient is ruled out because it would not have been possible to reproduce simultaneously the gamma-ray profiles at various longitude and latitude intervals.
- the source emission should contribute to the term B $\tilde{W}_{CO}$ in relation (1), because the gamma-ray source distribution, strongly peaked on the galactic plane, cannot be represented by $N(H_I)$ which has a quite broad latitude distribution. It is then likely that, if significant, the source population is distributed like W_{CO}.

III. THE LOCAL DIFFUSE EMISSION AS OBSERVED AT MEDIUM GALACTIC LATITUDE

As a consequence of the thickness of the gaseous galactic disc, the gamma-ray emission originating in the local interstellar gas can be observed at medium galactic latitude ($|b| \geq 10°$), i.e. in regions of the sky where there is no point-source contribution. Moreover, in the local galactic environment, the cosmic-ray density can reasonably be considered as uniform , even if one should also consider the impact of possible small scale inhomogeneities of the cosmic-ray density. It is then expected that the intensity of the high-energy gamma radiation observed at $|b| \geq 10°$ should give a straightforward estimate of the total gas column density, and consequently should help to depict the large scale structure of the local interstellar gas. Up to now the large scale appearance of the local gas has been derived from radio survey of the 21 cm emission line of the neutral hydrogen. But the amount of molecular hydrogen remains poorly known, as the H_2 column density can only be measured directly through molecular absorption of UV radiation from early type stars. Observations of interstellar molecules at radio frequencies could in principle be used as a tracer of H_2, in spite of observational and theoretical uncertainties, but at present only some dense nearby clouds are well mapped.

A way to illustrate the high degree of relationship between gamma-ray intensity and total gas column-density, is to show that gamma-ray intensity is strongly related to an other large scale total gas tracer as the amount of interstellar absorption derived from galaxy counts. Since the work of Lilley (1955), it has been recognized that a relationship exists between total gas and dust in the local interstellar medium. Early results in this field were based on Copernicus measurements (Bohlin, Savage and Drake, 1978), while interstellar absorption traced by the galaxy counts has been shown to be related to the total gas column density (see e.g. Strong and Lebrun 1981, and references therein). On the basis of the SAS-2 data (Fichtel et al. 1978), Lebrun and Paul (1983) have shown that at medium galactic latitudes, gamma rays are better related to the interstellar absorption, derived from galaxy counts, than to the atomic hydrogen column-density (fig.3). This implies that, in addition to the atomic hydrogen, a substantial fraction of the interstellar gas emits gamma rays and contains dust ; this fraction is likely to be molecular hydrogen. The same conclusion is supported by the COS-B data (Lebrun et al. 1982).

Such analysis gives the opportunity to map the regions where the molecular gas is particularly conspicuous, i.e. the regions where the observed gamma-ray intensity exceeds strongly the gamma-ray intensity expected from the neutral atomic hydrogen alone. The map of the local molecular gas, as derived by Lebrun and Paul (1983) using SAS-2 data, reveals in addition to some well-known closeby molecular clouds (as e.g. the Taurus and Rho Oph cloud complexes), a wide (angular size ~ 50°) concentration of molecular gas in the Aquila-Ophiucus-Sagittarius region. This nearby molecular complex, discovered by the gamma-ray study, has raised up radio observations. A complete CO survey of this region has been undertaken at the Columbia millimeter-wave telescope, and the first results of this survey testify that the predicted interstellar molecules are indeed present in this region of the sky (Lebrun and Huang 1982). In a similar way, a map of the local interstellar H_2 has been derived from the COS-B data by Strong et al. (1982). This map provides a completely sampled coverage for all galactic longitudes, revealing for the first time the local molecular hydrogen on the southern hemisphere.

It is well established from fig. 3 that a linear relation exists between gamma-ray intensity and total gas density :

$$I_\gamma(E) = N_H \mathcal{E}_\gamma (E)/4\pi + I_B(E) \qquad (2)$$

where N_H is the total gas column density, I_B the fraction of the radiation unrelated to the gas, and $\mathcal{E}_\gamma$ the gamma-ray emissivity per H atom through cosmic-ray interactions. It is well admitted that two processes contribute significantly to the gamma-ray emission : the interaction of cosmic-ray protons with the gas, and the cosmic-ray electron Bremsstrahlung. Protons contributing to high-energy gamma-ray emissivity through interaction with the interstellar matter are less affected by the solar modulation than cosmic-ray electrons producing the Bremsstrahlung radiation down to few tens of MeV. Therefore, it is justified to assume that the proton-interactions induced emissivity derived from the locally measured proton spectrum (Badhwar and Stephens 1977) can be used to assess the spectrum of the gamma-ray Bremsstrahlung emissivity and hence that of the progenitor electrons. Two similar attempts have been made to estimate the local interstellar electron spectrum, using the SAS-2 data (Lebrun and Paul 1983) and the COS-B data (Lebrun et al. 1982). In both cases, the derived cosmic-ray electron flux and energy spectrum imply the existence of a local electron flux which exceeds largely (below 1 GeV) the flux observed at the Earth.

IV. LOCALIZED SOURCES OF DIFFUSE EMISSION

Diffuse processes may also be at work in small scale objects, whose angular extent is so small (< 2°) that they cannot be resolved by the present generation of gamma-ray instruments. Among the 25 sources contained in the second COS-B catalog (Swanenburg et al. 1981), only four source have been identified. All the remaining sources -except one- are located very close to the galactic plane, they are obviously galactic. It has long been suggested that a class of gamma-ray source results simply from a significant concentration of gas and/or cosmic rays. Such concentrations can take place in the vicinity of young and massive stars. Also, as a galactic population, the clusters of young and massive stars -the OB associations- present some similarities with the gamma-ray sources as e.g. the very limited latitude extent. But a detailed study shows that only a sub-class of the OB associations may be the site of a copious gamma-ray emission. The young and massive star clusters are generally associated with dense and massive clouds, but only in some cases star clusters could be the site of an efficient cosmic-ray energization. Moreover the vicinity of such "active" OB associations may turn out to be a powerful source of gamma radiation, only if the gamma-ray producing cosmic rays are efficiently trapped in the dense surrounding medium.

The SNOB concept -supernova remnants physically linked with OB association- proposed by Montmerle (1979), provides a plausible scenario to interpret the gamma-ray emission from active OB associations. In this model, low energy particles injected by active stars pertaining to an OB association are accelerated by the passing shock induced by a supernova remnant expanding within the association. Thirty two SNOBs have been listed and 7 to 9 COS-B sources coincide with them (Montmerle and Cesarsky 1980). Several other SNOBs are situated in more extended regions of intense gamma-ray emission.

On the other hand, recent observations (see e.g. Snow and Morton 1976, Conti and Garmany 1980) have shown that 0 stars and B supergiants have strong stellar winds with typical velocities $V_w \sim 2000$ km s^{-1} and mass-loss rate $\dot{M} \sim 10^{-7}$ to 10^{-5} $M_{\odot}$ yr^{-1}. The adjustment process of the stellar-wind flow to the environment should involve a shock transition. This has prompted Cassé and Paul (1980) to propose stellar-wind terminal shocks as a site of acceleration of charged particles, extending an early suggestion of Jokipii (1968) for the solar wind. However most of the known OB associations do not contain stars emitting enough mechanical energy to be detectable as individual gamma-ray source by the COS-B satellite (Cassé, Montmerle and Paul 1981). On the contrary, the Carina Nebula, which comprises several OB associations and Wolf-Rayet stars -the most powerful mass losing massive stars- meets the visibility requirement. The presence of the gamma-ray source 2CG288-00 in the direction of the Carina Nebula forces to focus the attention on this rich concentration of young and massive stars.

Montmerle, Cassé and Paul (1981) have proposed that a modest fraction (< 10%) of the mechanical energy released by the stars in the form of supersonic stellar wind may be converted into cosmic-ray energy. The cosmic rays which are efficiently trapped by the resonant Alfvèn-wave scattering (e.g. Cesarsky 1980) in the large and dense ionized H_{II} region which surrounds the Carina star clusters, interact with the gas and produce the observed flux of gamma radiation. Some of the empirical parameters entering into this model, as e.g. the stellar-wind energy budget, are now substantiated by the recent UV observations of the 03 star HD93205 pertaining to the Carina Nebula (Laurent, Paul and Pettini 1982).

Note that cosmic-ray confinement is an essential ingredient in these models : for instance, in spite of the presence of numerous mass-losing young stars in the Orion complex, together with a huge concentration of dense interstellar gas, confinement by resonant Alfvèn-wave scattering is inefficient. No enhanced gamma-ray emissivity is expected within the Orion complex, as observed (Montmerle 1981).

The Carina complex, the richest concentration of young and massive stars can be considered as a candidate gamma-ray source. The same is for the closest aggregate of gas, dust and young stars : the Rho Oph cloud complex (fig. 4). The dense part of the cloud lies within the error circle of the COS-B source 2CG353+16. The observed flux is 4 to 10 times higher than the flux expected if, within the core of the cloud, the cosmic-ray intensity and energy spectrum are as observed in the solar vicinity (Simpson 1979, Cassé and Paul 1980, Bignami and Morfill 1980). A natural interpretation is that relativistic particles are accelerated within the cloud complex either by the supersonic stellar-wind mechanism (Cassé and Paul 1980, Paul, Cassé and Montmerle 1981) or by a close-by supernova shock -the North Polar Spur- (Morfill et al. 1981). However Issa, Strong and Wolfendale (1981) dispute the requirement of a higher cosmic-ray intensity within the cloud, noting that the surroundings of the cloud may also contribute to the observed flux of the gamma-ray source.

V. CONCLUSION

Detailed studies of the galactic gamma-ray emission are now possible, thanks to the COS-B observation. A comparison of the gamma-ray survey with the most extended CO survey together with an H_I survey has been used to show that a simple model, in which uniformly distributed cosmic rays interact with the interstellar gas, can account for almost all the gamma-ray emisison observed in the first galactic quadrant. A picture of the interstellar gas in the local galactic medium has been derived from gamma-ray observations at medium galactic latitudes, including a map of the local gas not in atomic form. The investigation of the local interstellar medium through gamma rays and interstellar absorption yields a quantitative estimate of the cosmic-ray electron flux and energy spectrum below 1 GeV. On a smaller scale, the detection of numerous localized gamma-ray sources have prompted the exploration of some particular phases of clusters of young and massive stars, where gamma rays can result from the interaction of cosmic rays produced in the vicinity of the star cluster and efficiently trapped in the dense surrounding medium.

Acknowledgements. I wish to thank François Lebrun for his help in preparing this review.

REFERENCES

Badhwar, G.D., and Stephens, S.A. 1977, Proc. of 15th ICRC, Plovdiv, 1, 198.

Bignami, G.F., and Morfill, G.E. 1980, Astr. Ap. 87, 85.

Bohlin, R.C., Savage, B.D., and Drake, J.F. 1978, Ap.J. 224, 132.

Cassé, M. Montmerle, T., and Paul, J.A. 1981, in Origin of Cosmic Rays, IAU/IUPAP Symp. n°94, G. Setti, G. Spada and A.W. Wolfendale (eds), p. 323.

Cassé, M. and Paul, J.A. 1980, Ap.J. 237, 236.

Cesarsky, C.J. 1980, Ann. Rev. Astr. Ap. 18, 289.

Cesarsky, C.J., and Paul, J.A. 1981, Nuclear Science Applications 1, 191.

Conti, P.S., and Garmany, C.D. 1980, Ap.J. 238, 190.

Dame, T.M., and Thaddeus, P. 1982, preprint.

Fichtel, C.E., Hartman, R.C., Kniffen, D.A., Thompson, D.J., Ogelman, H.B., Ozel, M.E., and Tümer, T. 1978, NASA-GSFC Technical Memorandum 79650.

Hermsen, W. et al., 1977, Nature, 269, 494.

Issa, M.R., Strong, A.W., and Wolfendale, A.W. 1981, J. Phys. G : Nucl. Phys. 7, 565.

Jokipii, J.R. 1968, Ap.J. 152, 799.

Laurent, C., Paul, J.A., and Pettini, M. 1982, Ap.J. 260, 163.

Lebrun, F. 1982, to be published in the Proc. of the Leiden Workshop on Southern Galactic Survey.

Lebrun, F. et al. 1982, Astr. Ap. 107, 390.

Lebrun, F. et al. 1983, preprint.

Lebrun, F., and Huang, Y.L. 1982, to be published in Ap.J.

Lebrun, F., and Paul, J.A. 1983, Ap.J. (in press).

Lequeux, J. 1981, Comments on Astrophysics 9, 117.

Lilley, A.E. 1955, Ap.J. 121, 559.

Mayer-Hasselwander, H.A. et al. 1982, Astr. Ap. 105, 164.

Montmerle, T. 1979, Ap.J. 231, 95.

Montmerle, T. 1981, Phil. Trans. R. Soc. Lond. A 301, 505.

Montmerle, T., Cassé, M., and Paul, J.A. 1981, preprint.

Montmerle, T., and Cesarsky, J.A. 1980, in Non Solar Gamma Rays, R. Cowsik and R.D. Wills (eds), Pergamon Press : Oxford, p. 61.

Morfill, G.F., Völk, H.J., Forman, M., Bignami, G.F., Caraveo, P.A., and Drury, L. 1981, Ap.J. 246, 810.

Paul, J.A., Cassé, M., and Montmerle, T. 1981, in Origin of Cosmic Rays, IAU/IUPAP Symp. n° 94, G. Setti, G. Spada, and A.W. Wolfendale (eds), p. 325.

Simpson, G. 1979, in Particle Acceleration Mechanism in Astrophysics, J. Arons, C. McKee, and C. Max (eds), American Isntitute of Physics : New York, p. 289.

Snow, T.P., and Morton, D.C. 1976, Ap.J. Suppl. 32, 429.

Strong, A.W., et al. 1982, Astr. Ap (in press).

Strong, A.W., and Lebrun, F. 1982, Astr. Ap. 105, 159.

Swanenburg, B.N. et al. 1981, Ap.J. 243, L69.

FIGURE CAPTIONS

Figure 1

Longitude profiles in two different latitude intervals of the observed gamma-ray emission for $E \geqslant 300$ MeV (error bars) compared with that expected from CO plus H_I (solid line) and from H_I alone (dotted line). The included background level C is indicated by the interrupted line.

Figure 2

Latitude profiles of the observed gamma-ray emission for $E \geqslant 300$ MeV (error bars), compared with that expected from CO plus H_I (heavy line) and from H_I alone (dotted line). The light line shows the profile expected from a pure line emission at $b = 0°$, normalized to the gas tracers expectations.

Figure 3a

Distribution of gamma rays (35 MeV $\leqslant E \leqslant$ 100 MeV) intensity as a function of atomic hydrogen column density deduced from 21 cm radio data. Upper left : acceptable (1σ below the maximum likelihood) values of the fitted parameters in the equation $I_\gamma = A \, N \, H_I + B$.

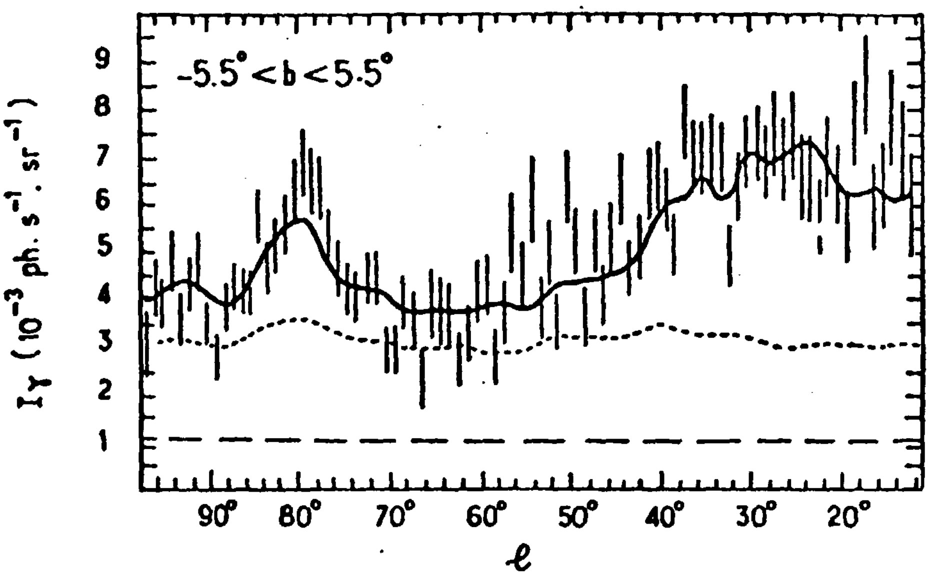
Figure 3b

Distribution of gamma rays 35 MeV $\leqslant E \leqslant$ 100 MeV) intensity as a function of the total gas column density estimated from galaxy counts. Upper left : acceptable (1σ below the maximum likelihood) values of the fitted parameters in the equation $I_\gamma = A \, N_H + B$.

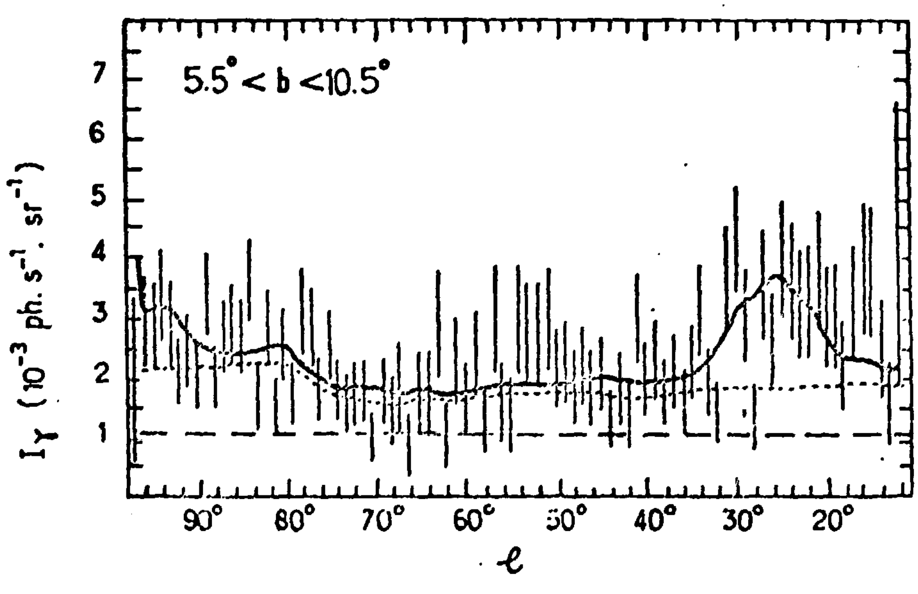
Figure 4

The region of the sky containing the Rho Ophiuchi gas cloud complex.

FIGURE 1



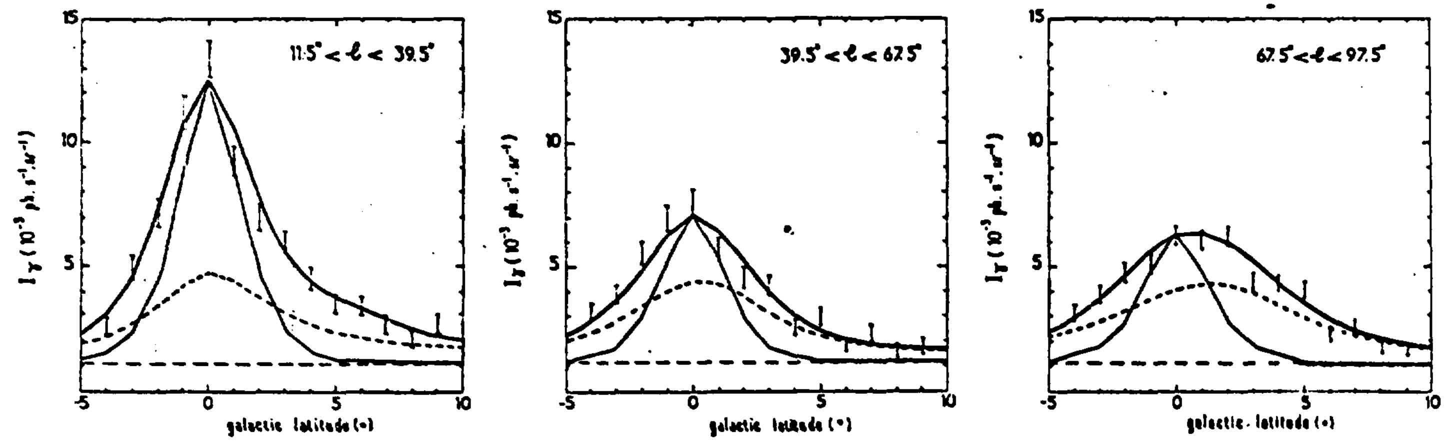
a



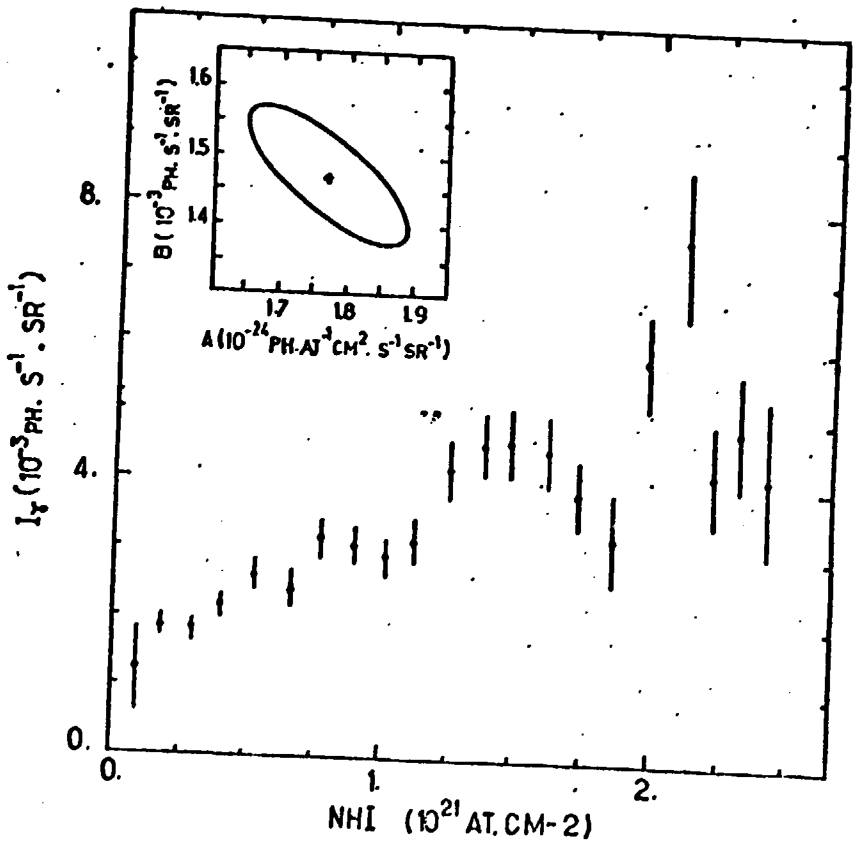
b

Fig 1

Fig 2

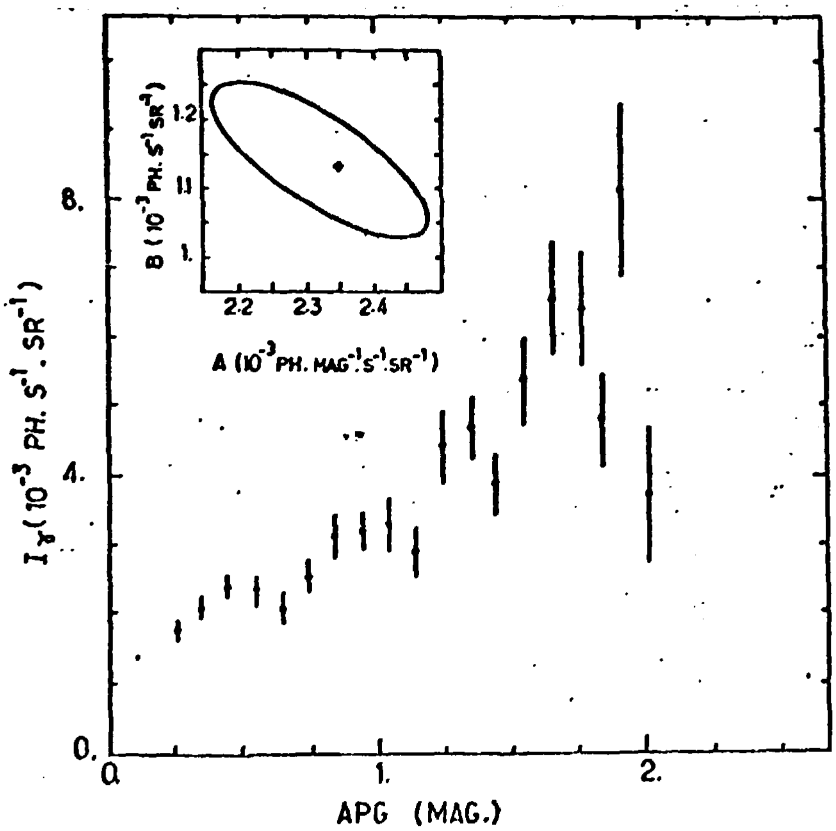


11.5° < ℓ < 39.5°
39.5° < ℓ < 67.5°
67.5° < ℓ < 97.5°
I_γ (10^{-3} ph.s^{-1}.sr^{-1})
galactic latitude (°)
15
10
5
-5
0
5
10



1.6
1.5
1.4
B (10^-3 PH. S^-1. SR^-1)
1.7
1.8
1.9
A (10^-24 PH. AT^-1 CM^2. S^-1 SR^-1)
8.
4.
0.
I_γ (10^-3 PH. S^-1 . SR^-1)
0.
1.
2.
NHI (10^21 AT. CM-2)

Fig 3a



8.
4.
0.
I_γ (10^{-3} PH. S^{-1}. SR^{-1})
0
1.
2.
APG (MAG.)
B (10^{-3} PH. S^{-1} SR^{-1})
1.2
1.1
1.
2.2
2.3
2.4
A (10^{-3} PH. MAG^{-1} S^{-1} SR^{-1})

Fig 3b

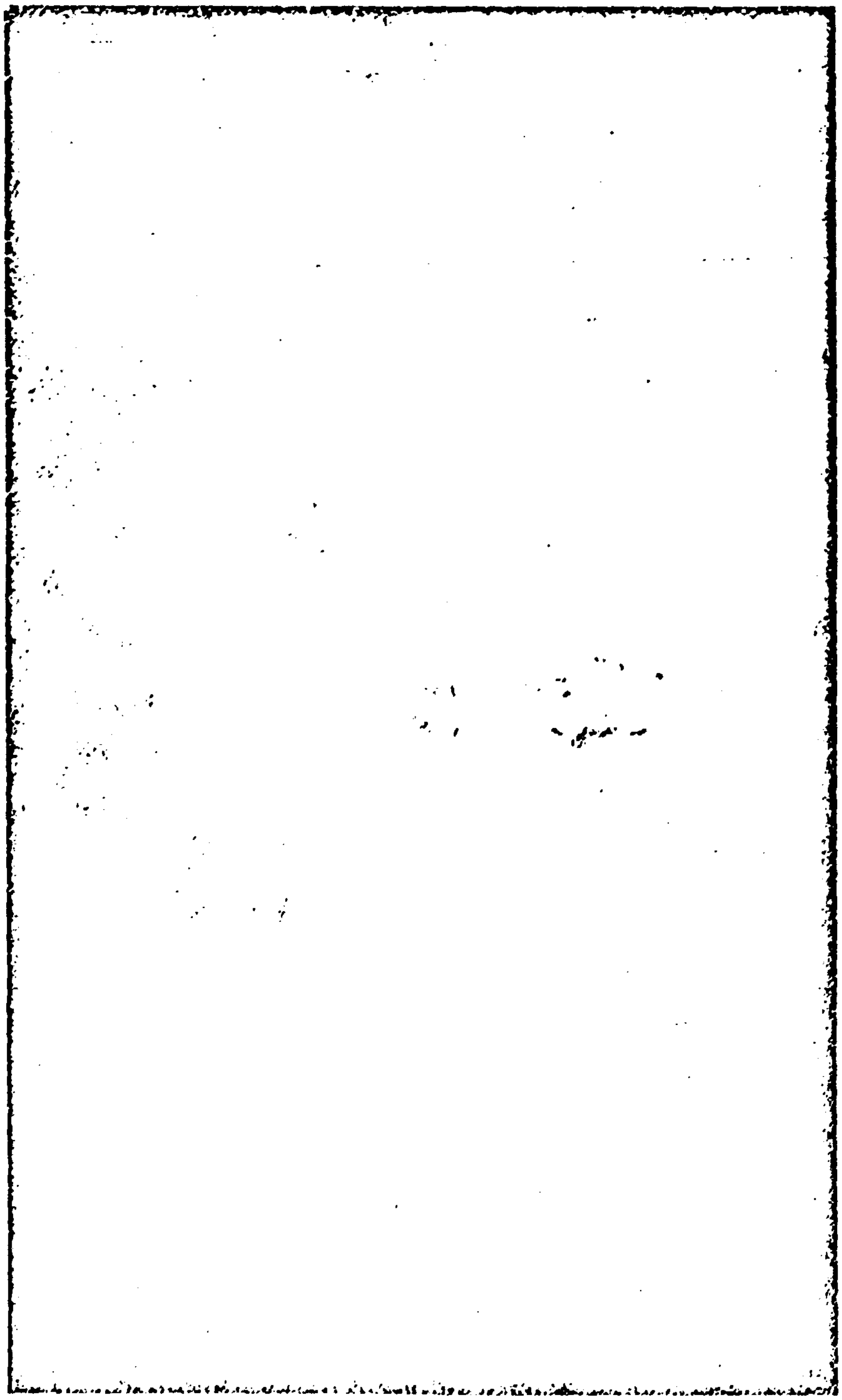


Fig 4