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Low-Latitude Galactic $\gamma $-ray Emission: A Probe, not a Proof [and Discussion]

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Low-latitude galactic γ-ray emission: a probe, not a proof

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The emission of high energy (above 70 MeV) γ-rays from the galactic disc has been mapped by the COS-B mission with unprecedented detail. The results for $|b| < 15°$ are seen to contain evidence of structures correlated with the Galaxy on various scales, from the 'grand design' down to granularities, showing that the diffuse interstellar medium, with its cosmic ray content, is well mapped by high energy γ-ray astronomy.

Two new detailed correlations are proposed, one local and one in the medium-distance scale, to corroborate the above statement. After discussing the importance of the discrete, unresolved sources also discovered by COS-B, an astrophysical process is sketched suggesting a scenario for enhanced emission in regions where interstellar medium shocks can accelerate cosmic rays.

Finally, the contribution of the nucleon and electron cosmic ray components in generating the galactic γ-rays in different energy ranges is briefly discussed, and seen to remain an open question.

1. INTRODUCTION

The brightest object in the high energy ($\gtrsim$ 70 MeV) γ-ray sky is the disc of our Galaxy: this simple astronomical result, first obtained by the OSO-3 mission, was confirmed by the SAS-2 satellite, and still, of course, holds after more than five years of COS-B data. However, after over one decade of active observational γ-ray astronomy, the question of the nature, or astrophysical origin, of such galactic radiation is still far from solved. In this paper, we shall address this question in the light of the best available data base, i.e. that stemming from 36 galactic observation periods of the COS-B mission, now being published by the Caravane Collaboration (Mayer-Hasselwander *et al.* 1981, hereafter denoted by M.H.*AL.*), confining our attention to the low latitude ($|b| \lesssim 15°$) results.

Basically, the dispute on the nature of galactic γ-radiation dwelt for years on two opposing views: (i) it is due to a truly 'diffuse' process, i.e. one originating from the interaction of components distributed in space, the energetic cosmic rays (c.r.) acting as projectiles, the interstellar matter and radiation fields as targets; or (ii) the diffuse aspect just results from the limited angular resolution of the γ-ray astronomy instruments, and in reality the emission is all concentrated in point-like objects, as is practically the case for medium energy (2–10 keV) X-ray astronomy, and for optical astronomy. The great advance that the COS-B data base allows us to make, is that we can say that both such 'radical' views are wrong: they probably originated historically from cosmic-ray and optical astronomers, respectively. From the data of the COS-B mission, given, for example, in M.H.*AL.*, and which will be presented here when appropriate, it appears beyond doubt that there exists *some* γ-ray emission due to interaction of c.r. with interstellar matter (i.s.m.): that is, some emission features (e.g. the extended emission in the Orion complex (see Caraveo *et al.* 1980)) cannot be mimicked by radiation from point-like sources. On the other hand, the COS-B mission itself has discovered the presence of unresolved (by the instrument's limited resolving power) sources of γ-rays, which could be compatible with emission by point-like objects. The debate has, since, shifted to how much of the *ca.* 6×10^{38} erg s^{-1}† emitted by the Galaxy in photons above about 100 MeV is due to each type of emission. In spite of much work (Bignami, Caraveo & Maraschi 1978 (B.C.M.); Protheroe *et al.* 1979; Rothenflug & Caraveo 1980; Riley & Wolfendale 1980), the question remains largely open. One can only posit, with safety, a lower limit to the contribution of sources from their raw flux values: the total flux in the recognized sources of Swanenburg *et al.* (1981) is less than about 5% of the total flux from the Galaxy as seen in M.H.*AL*.

In what follows, after dealing briefly with the problem of unresolved sources, treated more extensively elsewhere, we shall concentrate on the aspects of γ-ray astronomy that make it an excellent tracer of the product (cosmic ray energy density) × (interstellar matter number density). In this sense, γ-ray astronomy adds a new dimension to such existing and known tracers as

(i) the extinction of the visible light (actually tracing mostly the dust distribution);

(ii) the distribution of the soft (less than about 1 keV) X-rays, correlated with diffuse thermal processes;

(iii) the estimate (more-or-less direct) of the number of particles along the line-of-sight from measured antenna temperatures in radio astronomy.

It will be seen that new and very detailed correlations are possible, in one case even representing an independent discovery of a physical feature recently observed in the optical region. However, the c.r. energy density, with its possible variability, adds a dimension to the study of the i.s.m. with γ-rays, and this will be taken into account. In this respect, one must consider another point, coming out of the COS-B mission results: in spite of the experiment's energy-measurement capability, of the ample range covered (*ca.* 50 MeV to 5 GeV), and of the good statistics (by now), no clear spectral feature is seen in the data, like the much-awaited π^0-decay signature around 70 MeV. This only reminds us that when we speak of the c.r. we have to consider both protons and electrons and that it does not seem easy to disentangle the two components in the absence of other, independent measurements.

For the variability of the energy density of all the c.r., basic theoretical mechanisms are available; the detailed γ-ray data of COS-B provide one extra tool to check their quantitative applicability at least in the Sun's vicinity.

2. THE PROBLEM OF THE UNRESOLVED SOURCES (OR, THE UNRESOLVED PROBLEM OF THE SOURCES)

The second COS-B catalogue (Swanenburg *et al.* 1981) lists the set of 25 sources found in the COS-B data base available so far. It is important to emphasize that such a catalogue addresses only those peaks that are unresolved by the instrument, i.e. those (significant) excesses compatible with the instrument's point spread function (p.s.f.), measured by the pre-flight calibrations and confirmed by the flight data on the Vela pulsar. (The p.s.f. is discussed quantitatively by Hermsen (1980).) As mentioned earlier, the total flux contained in such excesses is a small fraction of that seen from the Galaxy. The 'sources' represent nevertheless a new class of celestial entities, so far unidentified. Without entering into much detail on the study of such sources, we note briefly that the problem of their nature has been approached from two sides: first, to study them as a population and secondly to try to identify them individually. As noted above, several authors have considered the collective properties of the sources and drawn conclusions

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† 1 erg s^{-1} = 10^{-7} W.

on their total contribution to the galactic γ-ray luminosity, as well as to the possible non-homogeneous nature of the sample, at least from the appearance of their $\lg N$–$\lg S$ graph (Bignami & Caraveo 1980). As an example, figure 1 shows the contribution of sources, as computed by B.C.M. on the basis of the earlier catalogue of Hermsen *et al.* (1977), being dependent on their galactocentric distribution; in the same model, B.C.M. predicted the number of sources in the COS-B catalogue to be 25 ± 7. The type of work mentioned above is independent of the nature of the sources; other authors have attempted to model the galactic emission on the basis of astrophysical assumptions on the source population.

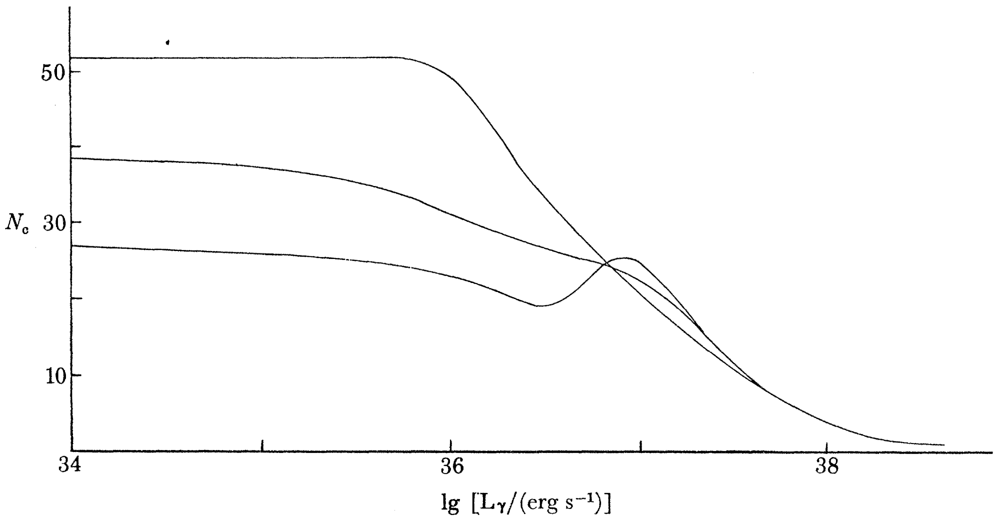

FIGURE 1. The number of calculated observable sources N_c as a function of their individual luminosities (above 100 MeV), for a total luminosity of the Galaxy of 4×10^{38} erg s^{-1}. Three galactocentric distributions are shown. (Taken from B.C.M.)

As to the individual identifications, many interesting proposals have been put forward for possible counterparts (Lamb 1978; Montmerle 1979; Van den Bergh 1979, Strong 1977; Protheroe *et al.* 1979; Gregory *et al.* 1979; Maraschi & Treves 1980; Bignami *et al.* 1976; Cesarsky *et al.* 1976; Montmerle *et al.* 1980; Bignami & Morfill 1980; and many others). A definite proof is lacking, however, except for the obvious cases of the two pulsars in Crab and Vela, discovered by SAS-2 and confirmed by COS-B. Another approach also actively pursued has been that of searching the COS-B error boxes at other wavelengths, also without definite results so far but with encouraging possibilities (Bignami 1980; Hermsen 1980; Caraveo, this symposium; Sieber *et al.* 1979). There have also been interesting astronomical side effects: the discovery of a new quasi-stellar object (Apparao *et al.* 1978) and of a twin set of X-ray pulsators (Lamb *et al.* 1980); the discovery and detailed study of the peculiar radio star LSI + 61.303° (Gregory *et al.* 1979, Bignami *et al.* 1980); and the destruction of a postulated satellite galaxy to our own (Bignami *et al.* 1977).

3. A HIERARCHY OF STRUCTURES

The presence of structure in the low latitude galactic γ-ray emission is best shown in figure 2, adapted from M.H.*AL*. The γ-ray isophote representation, with its implied degree of smoothing, precludes the precise observation of the catalogued sources, but is ideal for studying features

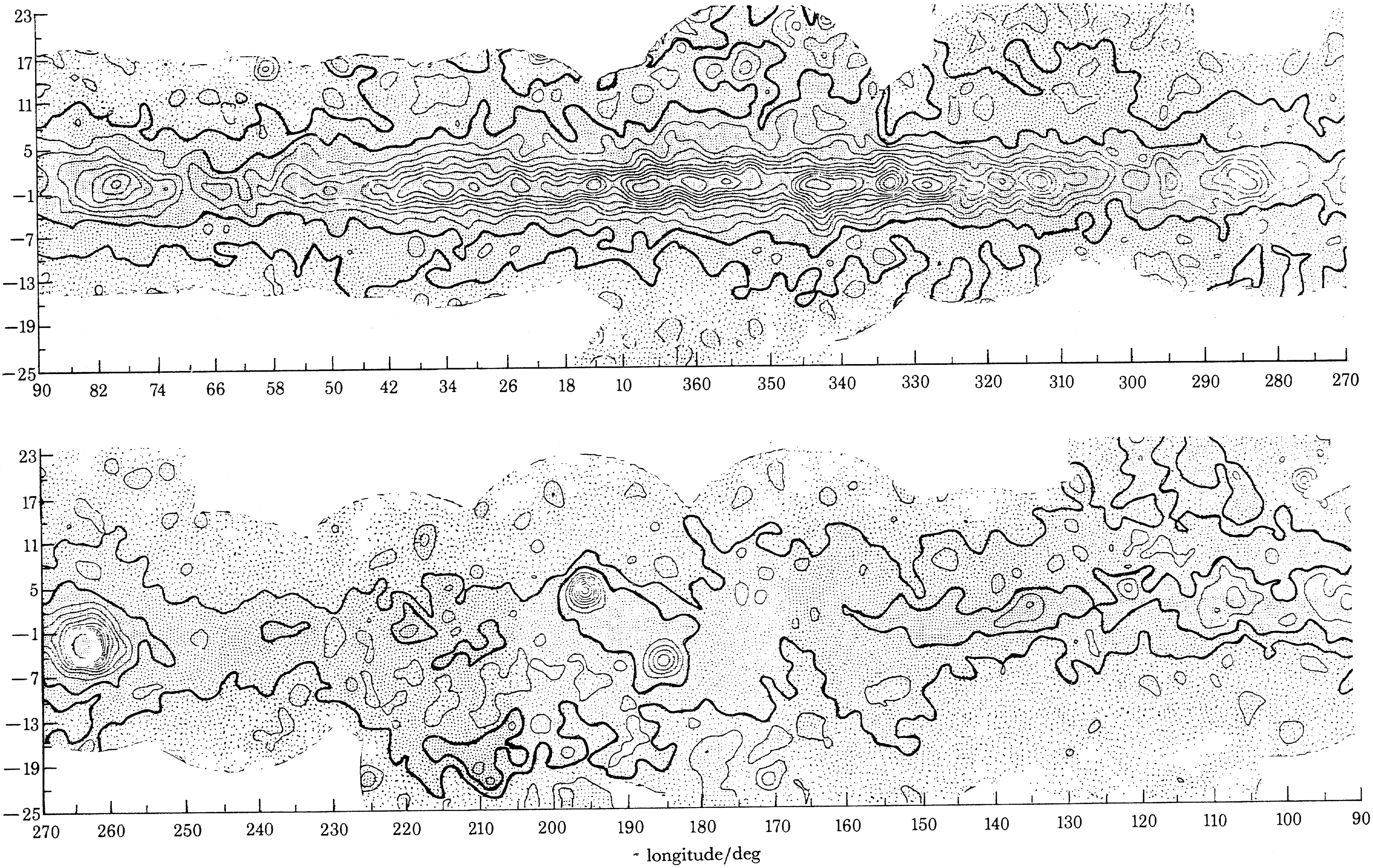

FIGURE 2. Gamma-ray isophote map for the energy range 70–5000 MeV, obtained with 36 observation periods of COS-B. The data are taken from M.H.*AL*., where the smoothing algorithm is described. An idea of the h.p.b.w. can be gained by looking at the Vela source (see also text).

extended on various angular sides. An idea of the half-power beam-width (h.p.b.w.) for figure 2 can be gained by looking at the Vela source position: for dynamical range reasons, the flux from the source is truncated at about half its peak value.

Following M.H.*AL.*, one can describe figure 2 in terms of three levels of structure:

(i) a *large scale* one, 'locking' the γ-ray galaxy to the grand design of the spiral structure, by now well known and already quite apparent in the SAS-2 data (see, for example, Fichtel *et al.* 1975);

(ii) *a medium distance* (*scale*) one, the best example of which is in the Cas-Cep-Per region, where the γ-ray emission seems to follow quite well the HI distribution of the Perseus arm (Weaver 1974), and also the recent CO data on the same region by Cohen *et al.* (1980);

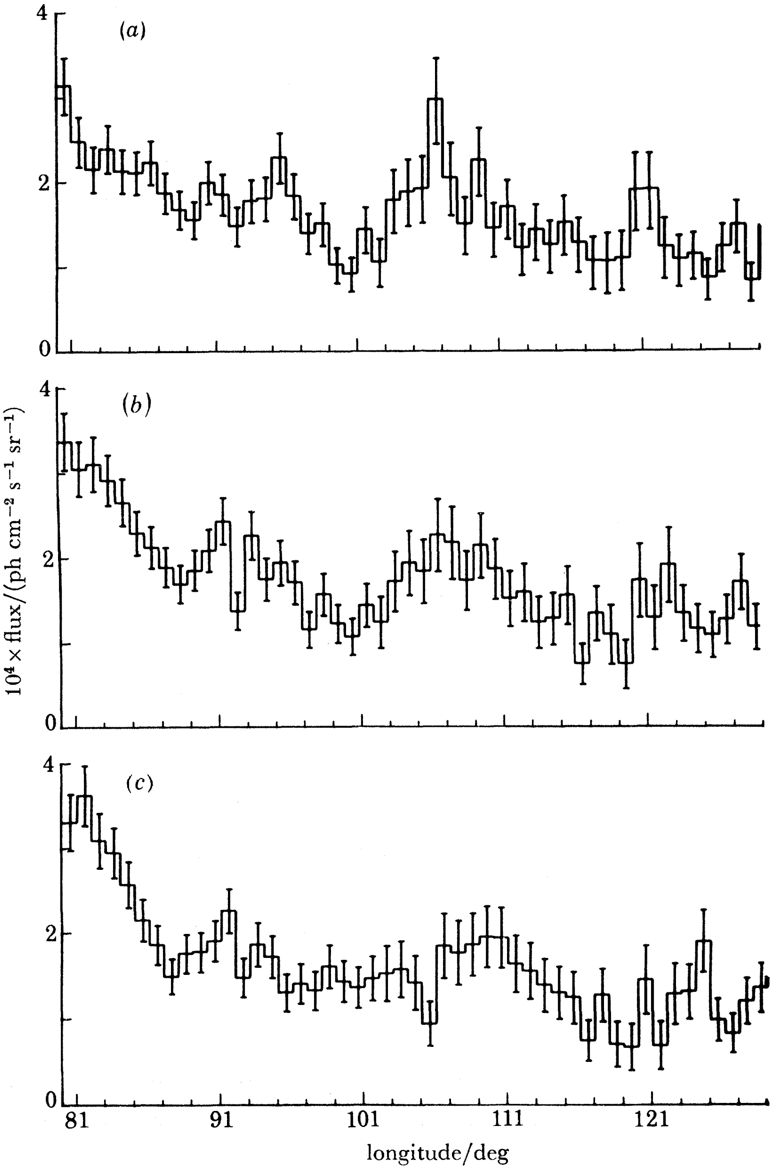

FIGURE 3. Longitude profiles for various latitude integrations – COS-B data for $150 < E < 5000$ MeV. Latitude integrations are between (*a*) 1° and 6°, (*b*) $-1°$ and 4°, (*c*) $-3°$ and 2°.

(iii) a *local* set of structures, featuring the well known excess from the Gould Belt first seen by SAS-2 (Fichtel *et al.* 1975; Hartman *et al.* 1979) and now with the two 'hot spots' of ρ-Oph and Orion, plus the general correlation outlined by Lebrun & Paul (1980).

Another way of presenting the various structures in the low latitude γ-ray data is shown in figure 3. Here the high energy flux longitude profiles are shown for various latitude integrations in the $80° < l < 130°$ region. In these profiles one can note, from left to right: (i) a wide decrease at $81° < l < 88°$ from the complex Cygnus region, a broad-structured enhancement starting at $l \approx 70°$; (ii) what looks like a relatively narrow peak at $91° < l < 92°$ but which does not pass the source-confidence test of Swanenburg *et al.* (1981) and therefore is not included in the second COS-B catalogue; (iii) a narrow peak at $l \approx 95°$ and positive b, which is accepted by the source-selection criteria and is, in fact, 2CG095+04 ($l = 95.5°$, $b = 4.2°$, error radius $= 1.5°$); (iv) a wide enhancement for $103° < l < 113°$, obviously too wide to be consistent with one unresolved source, which we shall call the CASCEP excess and return to later; (v) a clear narrow excess at $l \approx 121°$ and positive b, which is also accepted as a source and is listed as 2CG121+04 ($l = 121.0°$, $b = 4.0°$, error radius $= 1.0°$). The set of profiles in figure 3 can thus be considered morphologically as a *complete example* of the galactic γ-ray emission, at least as seen by current instrumentation. Similar situations could be presented for the Perseus or Carina or Circinus regions, and in fact for most of the galactic disc.

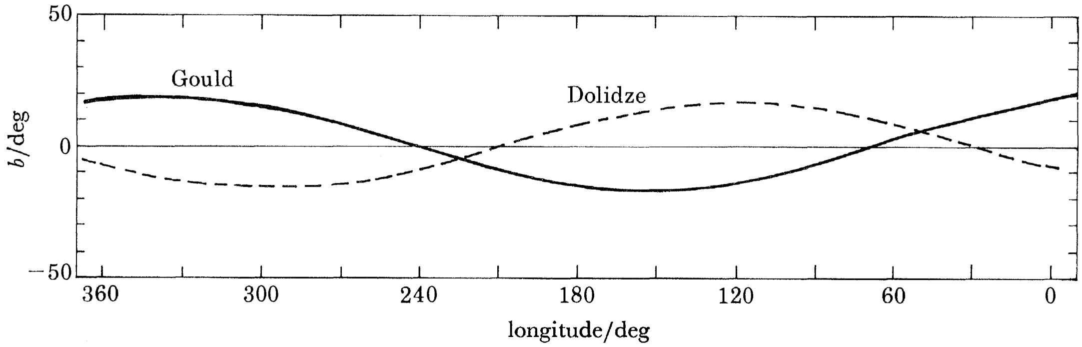

FIGURE 4. The two local belts (suspenders?) of Dolidze (1980) and Gould, in galactic coordinates.

4. GAMMA-RAYS AS I.S.M. TRACERS

(a) *Observational: new detailed correlations*

The correlations with galactic structure outlined above, and discussed more extensively in M.H.*AL.*, can be augmented with two further examples: the 'Dolidze belt' and the CASCEP excess.

(i) *The 'Dolidze belt'*

Dolidze (1980) has recently reported the discovery of a new structural feature in the Sun's local environment, similar to the familiar Gould Belt but quite independent of it. It is a disc-shaped structure of young stars, OB-, T- and R-associations, and various types of diffuse nebulae and matter, which is orientated approximately along the line $l = 117°$ to $l = 297°$ and inclined at 16–17° to the $b = 0°$ plane. Such a structure should show a sinusoidal curve when projected in the *l*, *b*-plane. Figure 4 shows its trace together with the canonical Gould-Belt pattern. Since some of the data are based on the Hubble zones of avoidance (for extragalactic work), it is not surprising to find much of the Dolidze-Belt pattern in the map of the H_2 column density derived from galaxy counts by Strong & Lebrun (1980).

The pattern of the Dolidze belt explains naturally the inconsistencies between the M.H.*AL.* γ-ray isophote picture and the Gould Belt. These are: the very significant excess in the region $100° < l < 140°$ and $10° < b < 20°$ (noted in M.H.*AL.*) and the less obvious excess for $270° < l < 330°$ and $-20° < b < -10°$. For this last region, one must note that the data base is severely limited by the Earth-aspect angle of the experiment axis because of the orbital parameters of the COS-B satellite.

(ii) *The* CASCEP *excess*

The region of the galactic disc contained in $107° < l < 113°$, $0° < b < 4°$ has been the subject of radioastronomical studies (Assousa *et al.* 1977; Read 1980*a*, *b*; Cohen *et al.* 1980) since it became apparent that it contained evidence suggestive of ring-like structures or supernova remnants (s.n.r.). The result of the most recent analysis of the data (Read 1980*b*) is as follows. The region contains, in fact, two quasi-spherical expanding shells. The first, near 0 km s^{-1} (l.s.r.) is associated with the shell of gas near the Cep OB3-association, at a distance of *ca.* 730 kpc and with a diameter of *ca.* 100 pc. The feature is centred at $l = 111°$ and $b = 3°$, and is, in fact, an exceedingly thin (0–5 pc) ring. Assousa *et al.* (1977) and Read (1980*b*) note that it could be compatible with an expanding shell (velocity $\gtrsim$ 20 km s^{-1}) of a type II s.n.r., about 4.3×10^5 years old, but also that a similar feature could be mimicked by a stellar wind 'bubble'. However, when compared positionally with the broad excess in figure 3, its coincidence with this particular i.s.m. feature does not seem completely satisfying, even allowing for the dimensions of the bump and its possible inhomogeneities. Also, if one has in mind a 'standard', *à la* Black & Fazio (1973), production mechanism for the γ-rays, at the distance quoted, the total mass of gas seen by solar-system-like cosmic rays would have to be of the order of $10^5\ M_\odot$, a value far too great for such a thin shell.

Read (1980*a*) goes on to note that the region also includes a second ring feature which appears to be an expanding shell, but is more distant, i.e. with $V_{\text{l.s.r.}} = -35$ km s^{-1}. It may or may not belong to the Perseus arm (at 2 kpc) which has been recently mapped in CO in good detail (Cohen *et al.* 1980). The maps show a complex of clouds at approximately the same longitude, and the expanding shell may even be interacting with some of the cloud material in the arm. The expansion velocity is evaluated as *ca.* 15 km s^{-1}, consistent with an old (*ca.* 1–2×10^6 years) supernova remnant. The neutral hydrogen mass *in the shell itself* (only about 2–5 pc thick) is *ca.* $10^4\ M_\odot$; of course the amount of matter with which the shell is interacting can be much greater. Here again the positional coincidence with the broad γ-ray excess is only loose, and the energetics insufficient, on the basis of a standard mechanism. On the other hand, the broad γ-ray enhancement exists and is very significant, and, because of its size, must have an explanation in terms of 'diffuse' mechanisms connected with some galactic structure. The two expanding shells in the region (partly overlapping in projection), and the presence of massive molecular complexes discovered in the CO data of Cohen *et al.* (1980) would be natural candidates to invoke in this otherwise rather calm galactic region.

(*b*) *Theoretical: on shocks, cosmic rays, i.s.m. and γ-rays*

Wolfendale (1980) has shown pictorially the main limit of the Black & Fazio (1973) mechanism (i.e. of the interaction of c.r. as seen, or rather imagined, demodulated at the Earth with the i.s.m. clumped in clouds); it is not elastic enough in that, given the flux observed, only those clouds obeying the mass–distance-squared relation can be considered as candidate sources.

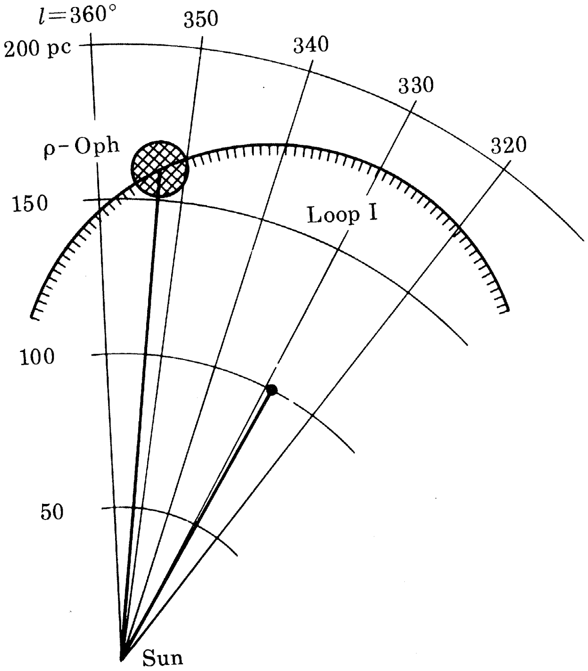

FIGURE 5. Suggested geometry for $b=17°$, well within the observational constraints, showing the interaction of the s.n.r. shock wave of the North Polar Spur (Loop I) and the cloud near ρ-Oph. (Taken from Morfill *et al.* 1981.)

True, some reduction in efficiency was possible by postulating a non-complete penetration of the cloud by the c.r. However, Strong & Skilling (1977) and Cesarsky & Völk (1978) have shown that such an *impotentia penetrandi* does not significantly apply to those c.r. energetic enough to produce γ-rays. To increase the number of possible candidate cloud complexes, Wolfendale (1980) postulates a factor F, between one and four, by which one would have to multiply the c.r. energy density at the cloud (with the possible exception of the complicated situation in the galactic centre (see Wolfendale & Worrall 1977)). In fact such a gradient in the c.r. *on a small scale* would seem to be definitely needed to explain the contrast level present in the detected granularity of the γ-ray flux from the Galaxy. Montmerle (1979) has proposed such a mechanism based on the SNOB-association interaction (effectively locally increasing the c.r.) and Cassé & Paul (1980) also proposed the provision of the necessary energy increase from the output of active, young stars which are frequently present in cloud complexes. Bignami & Morfill (1980), in considering the identification of 2CG 353+16 with the cloud complex associated with the star ρ-Oph, also recognize the need for an increase (by a factor of about 3) of the γ-ray yield of the cloud, obtainable with a local c.r. acceleration. Morfill *et al.* (1981) go a step further, and for ρ-Oph propose the following scenario: the North Polar Spur (the well known radio Loop I), which is in fact an expanding s.n.r., is reaching the vicinity of the cloud (see figure 5 taken from Morfill *et al.* (1981) and figure 6 of Davelaar *et al.* (1980)) so that the c.r. accelerated at the (large) s.n.r. shock wave are able to illuminate the cloud completely and produce the required γ-ray flux. It is emphasized that the accelerated c.r. are the *ambient* ones, and the acceleration is of the type proposed, for example, by Axford *et al.* (1977), Bell (1978*a*, *b*) and Blandford & Ostriker (1978). So long as the shock speed V_s exceeds the Alfvén speed of the i.s.m. (which is practically the situation in a hot, tenuous medium), the shock acceleration is efficient and can be described (Axford *et al.* 1977) by

$$F_s(p, p_0) = \frac{L}{L-C} F_0 (p/p_0)^{-3C} \left[1 - \frac{C}{L} (p/p_0)^{-3(L-C)}\right], \tag{1}$$

where $F_0 (p/p_0)^{-3C}$ is the ambient c.r. flux and $3C = 4.6$, from the spectral measurements at the Earth; $L \equiv V_s/(V_s - v)$, where v is the plasma velocity behind the shock. If, for example, $L = \frac{4}{3}$, in equation (1) the spectral shape goes from $p^{-4.6}$ to p^{-4} as $p \gg p_0$: relatively high energy particles can be quite efficiently accelerated. This well known result has been applied by Morfill *et al.* (1981) to the case of the Loop I s.n.r., and can be used generally, as follows. Consider the amount of c.r. energy added to the remnant per unit time:

$$dE/dt = f\epsilon_{c.r.}\, 4\pi r_s^2(t)\, V_s(t), \tag{2}$$

where $\epsilon_{c.r.}$ is the familiar 1 eV cm^{-3}, r_s is the radius of the s.n.r. (or of the shock) and f is the factor accounting for the enhancement at the shock. The c.r. adiabatic energy losses due to the expansion can be evaluated from the relation

$$PV^{\gamma} = \text{const.}$$

between the pressure P and volume V of the s.n.r., and $\gamma = \frac{4}{3}$ for relativistic particles. For V_0 expanding to V the energy decreases from E_0 to E:

$$E/E_0 = (V_0/V)^{\gamma-1},$$

so that the total c.r. energy accumulated in an s.n.r. between times t_1 and t_2 is

$$E_{c.r.}(t_1, t_2) = \int_{t_1}^{t_2} dt\, \frac{dE(t)}{dt} \left(\frac{V(t)}{V(t_2)}\right)^{\gamma-1}. \tag{3}$$

If the remnant is old enough to be in the Sedov phase, then

$$r_s = \left(\frac{2E_{s.n.}}{\mu n}\right)^{\frac{1}{5}} t^{\frac{2}{5}}, \tag{4}$$

where μ is the mean molecular weight of the plasma and n is the ambient density in particles cm^{-3}. On the assumption of equipartition of the kinetic energy of the medium upstream of the shock into (i) thermal energy, (ii) c.r. energy enhancement, and (iii) electromagnetic energy, one can combine equations (2), (3) and (4) to yield

$$E_{c.r.}(t_1, t_2) \propto E_{s.n.}[1 - (t_1/t_2)^{\frac{2}{5}}],$$

i.e. the c.r. energy content of the remnant depends slowly on time for $t_2 \gg t_1$, if t_1 is the start of the Sedov phase (in practice, several hundred years). Substituting typical values for an s.n.r. expanding in a hot medium ($E_{s.n.} = 10^{51}$ erg, $n = 10^{-2}$ cm^{-3}), as is the case for the North

Polar Spur, Morfill *et al.* find that the time taken for the c.r. energy content to increase by about a factor of 3 with respect to the local value (Wolfendale's F) is *ca.* 2×10^5 years, in excellent agreement with the derived age of Loop I (Davelaar *et al.* 1980 and references therein).

5. CONCLUSION

Shocks in the i.s.m. can produce localized c.r. enhancements and as such are ideal tools for generating the observed small (or medium) scale granularities in the M.H.*AL*. data. They are particularly handy since it has been shown that quite normal, if moderately old, sizeable s.n.r. can produce very adequate shock fronts. On the other hand, it is not proposed to explain fully, on their basis, the *exceptional* phenomenon of the γ-ray sources, but rather the usual, i.e. the 'tormented', emission from the disc. For the unresolved sources themselves, more exotic mechanisms are to be invoked to explain the 10^{-10} erg cm^{-2} s^{-1} hard photons that reach us from each of them. Of course, s.n. and c.r. may be involved, as in the case of SNOB associations, which are special objects, or rather extreme cases (albeit attractive), and certainly can provide amply the energetics: a possible contribution to the CASCEP excess due to the presence of the Cep-OB3-association can be considered (Montmerle 1979), even if it seems difficult to tell the whole story with it.

After having discussed the possibilities of small scale gradients in c.r. and their importance in γ-ray astronomy, it is perhaps appropriate to turn for a moment to the existence of a large scale, galactic gradient. Here, the COS-B mission has not added significantly to the data from SAS-2: the early works (e.g. Bignami & Fichtel 1974; Paul *et al.* 1975), as well as more recent ones summarized by Wolfendale (1980), all agree that some type of large scale gradient in the c.r. must exist. One of the important outcomes of about a decade of γ-ray astronomy is that the gigaelectronvolt cosmic rays, where the bulk of the 1 eV cm^{-3} of energy density lies, show various types of anisotropies tied to the i.s.m. The COS-B mission has finalized, indeed it has emphasized, this conclusion with the all-important result (in this respect) of the local i.s.m. being so clearly mappable in γ-rays; which had been predicted and hoped for since the intriguing but not completely sufficient results of SAS-2 (Puget *et al.* 1976; Lebrun & Paul 1979).

Another result of the COS-B mission has been mentioned in this context, and this is the spectral analysis of the radiation from the plane, given in the preliminary data of Paul and now in M.H.*AL*. With the good statistics now available, COS-B can make two quite definite statements: (*a*) the spectral shape of the radiation does not vary significantly with longitude and (*b*) it is definitely incompatible with the expected π^0-originated spectrum in the 70–5000 MeV range, because it appears consistent with a power law, of index not too different from -2. Note that COS-B has measured individual spectra from sources that are quite varied (Wills *et al.* 1980), so that the distinct π^0 signature could not have escaped detection, if present.

High energy γ-ray astronomy was started with the aim, amongst others, of finding evidence of the galactic distribution of the proton component of cosmic rays: the spectral measurements show that this is not (at least immediately) possible. The power-law shapes suggest the presence of a substantial component possibly due to the bremsstrahlung of c.r. electrons, of a few hundred megaelectronvolts, against the i.s.m. This has been considered in the past (Fichtel *et al.* 1976; Cesarsky *et al.* 1978; Wolfendale 1980 and references therein) and seems definitely

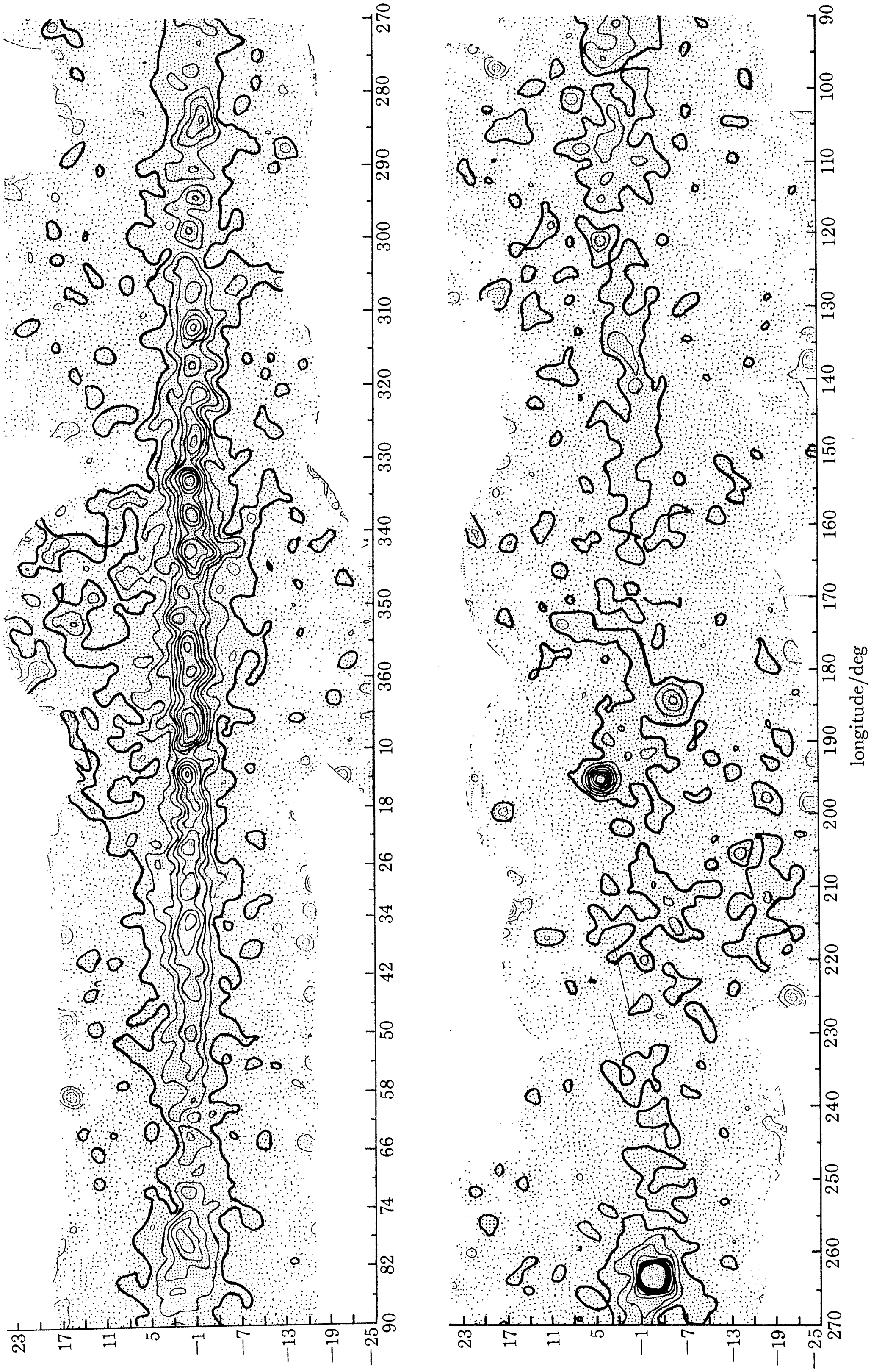

FIGURE 6. As for figure 2, but for the energy range 300–5000 MeV.

supported by the COS-B data. To evaluate quantitatively the two components seems difficult, and the result is probably not unique; some insight might be gained by inspection of figure 6. Here, as in M.H.*AL*., the γ-ray isophotes are given; however, they only refer to photons in the 300–5000 GeV range, where it is reasonable to expect the proton-induced component to dominate. One notes a remarkable similarity with figure 2, which contains all photons above 70 MeV, when allowance is made for the variation in angular resolution. The only very appreciable difference is noted in the two sources Crab and 'Geminga' (2CG 195 + 4), whose relative importance differs. This similarity on the one hand shows that we are not dealing with a totally different type of origin for the photons, and on the other supports the idea that the responsible particles (gigaelectronvolt protons) are sensitive to the i.s.m. distribution. Another approach comes from high latitude *measurements* of the emissivity, q_γ, per equivalent H-atom, performed for the SAS-2 data (Fichtel *et al.* 1978; Hartman *et al.* 1979) and now also for COS-B (Caraveo *et al.* 1980; Lebrun *et al.* 1981).

Such measured values can be compared with the predicted ones (see, for example, Stecker 1973; Stephens & Badhwar 1981) for the demodulated proton spectrum: they seem to account for about half the measured values.

Altogether, the Salomonic assumption that protons and electrons contribute about equally to figure 2 can stand as reasonable or at least cannot be easily disproved, and clearly they contribute by interacting with the diffuse i.s.m.

Cosmic rays are still very important to γ-ray astronomy (and vice versa); COS-B has added the unexpected bonus of several dozen γ-ray objects which might be the key to something new in high energy astrophysics.

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Discussion

A. W. Wolfendale, F.R.S. (*Physics Department, The University, Science Laboratories, South Road, Durham DH*1 3*LE, U.K.*). I have two comments about ρ-Oph and Professor Bignami's explanation that the γ-rays from it have come from cosmic ray interactions in the cloud, the cosmic rays having been accelerated by a supernova shock:

(i) Is it not very unlikely that the shock has arrived just at the right place at the right time?

(ii) The energy spectrum of accelerated cosmic rays seems to be very different from that needed to give the observed γ-ray spectrum.

G. F. Bignami. A complete description of the case for the interaction between the cloud near the star ρ-Oph and the North Polar Spur (Loop I) supernova remnant, with subsequent increase in the γ-ray yield of the cloud can be found in the quoted paper by Morfill *et al.* (1981). For a concise answer to the two questions:

(i) The soft X-ray data of Apparao *et al.* (1978) from the SAS-3 mission exclude the local, hot, X-ray-emitting region extending significantly beyond ρ-Oph, or it would be seen in absorption, which it is not. On the other hand, the shock-induced cosmic ray spectral hardening begins to be felt a few parsecs ahead of the shock, the exact value depending on the local value of the diffusion coefficient. If we allow for a total of *ca.* 10 pc relative positional uncertainty between the cloud and the shock, which travels at 350 km s^{-1}, we find that the time scale of the process is not less than 3×10^4 years.

(ii) One has to note that equation (1) is given in phase space: going back to the space where measurements are actually made implies multiplying by p^2. It is then seen that the acceleration leads to multiplying by p^{-2} to $p^{-2\cdot 6}$, and no spectral contradiction with what little is measured in γ-rays is apparent.

N. Lund (*Danish Space Research Institute*, *Lundtoftens* 7, 2800 *Lyngby*, *Denmark*). Professor Bignami has discussed the possibility that cosmic rays may be reaccelerated by a passing supernova shock wave.

I would like to remind the reader that it is now established beyond doubt that different chemical elements in the cosmic radiation have different energy spectra. This fact rules out the bulk of the cosmic rays having been reaccelerated significantly by interaction with shock waves as this would produce similar energy spectra for all elements. However, it does not of course rule out shock acceleration as the initial acceleration mechanism in specific sources.

G. F. Bignami. The comment is appropriate for the bulk of the cosmic rays in the Galaxy. The model presented above refers, however, to special and limited situations, for example in the North Polar Spur and the ρ-Oph cloud. In view of the relatively small amount of acceleration necessary to account for most of the γ-ray enhancements, it is certainly true that in such specific sources shock acceleration can happen.