SECTION II.4

THE HIGH-ENERGY COMPONENT

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C.J. Cesarsky (top) and R. Beck (bottom) presenting their review papers
CFD

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HIGH-ENERGY GALACTIC PHENOMENA AND THE INTERSTELLAR MEDIUM

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GAMMA RAYS AND THE GALACTIC DISTRIBUTION OF COSMIC RAYS

Gamma rays of energy in the range 30 MeV-several GeV, observed by the satellites SAS-2 and COS-B, are emitted in the interstellar medium as a result of interactions with gas of cosmic-ray nuclei in the GeV range (π° decay γ rays) and cosmic-ray electrons of energy > 30 MeV (bremsstrahlung γ rays). W. Hermsen has presented at this conference the γ ray maps of the Galaxy in three "colours" constructed by the COS-B collaboration; the information in such maps is supplemented by radio-continuum studies (see lecture by R. Beck), and is a useful tool for studying the distribution of gas, cosmic rays (c.r.) and magnetic fields in the Galaxy. The variables in this problem are many:large-scale ($\sim$ 1 kpc) and small-scale ($\sim$10 pc) distributions of c.r. nuclei, of c.r. electrons, of atomic and molecular hydrogen, of magnetic fields, fraction of the observed radiation due to localized sources, etc. Of these, only the distribution - or at least the column densities - of atomic hydrogen are determined in a reliable way. Estimates of the amount of molecular hydrogen can be derived from CO observations or from galaxy counts. The radio and gamma-ray data are not sufficient to disentangle all the other variables in a unique fashion, unless a number of assumptions are made (e.g. Paul et al. 1976). Still, the COS-B team has been able to show that :
a) there is a correlation between the gamma-ray emission from local regions, as observed at intermediate latitudes, and the total column density of dust, as measured by galaxy counts. The simplest interpretation is that the density of c.r. nuclei and electrons is uniform within 500 pc of the sun, and that dust and gas are well mixed. Then, γ rays can be used as excellent tracers of local gas complexes (Lebrun et al. 1982, Strong et al. 1982).
b) In the same way, the simplest interpretation of the γ-ray emission at energy > 300 MeV from the inner Galaxy, is that c.r. nuclei and electrons are distributed uniformly as well : there is no need for an enhanced density of c.r. in the 3-6 kpc ring ; on the contrary, even assuming a uniform density of c.r., the γ-ray data are in conflict with the highest estimates of molecular hydrogen in the radio-astronomy literature (Mayer-Hasselwander et al. 1982).

H. van Woerden et al. (eds.), The Milky Way Galaxy, 225–233.

c) In the outer Galaxy, the gradient of c.r. which had become apparent in the early SAS-2 data can now, with COS-B data, be studied in three energy ranges. A gradient in the c.r. distribution is only required to explain the low-energy radiation, which is dominated by bremsstrahlung from relativistic electrons (Bloemen et al., in preparation).

Thus, as the COS-B data have been gaining in statistical accuracy through the 7.5-year lifetime of the mission, they have not confirmed (but not really ruled out either) one of the main early findings of gamma ray astronomy : the existence of gradients in the distribution of galactic c.r. nuclei. Gamma-ray observations do not stand anymore in the way of the tenants of the hypothesis of the universality of c.r. nuclei.

GAMMA-RAY SOURCES : A NEW GALACTIC POPULATION ?

COS-B has also observed - and the COS-B team is still studying - a number of localized and extended γ-ray sources. The Orion molecular cloud complex is the best studied of the extended sources. The correspondence between the γ-ray map and the CO map is excellent ; the emission is as expected for a uniform c.r. density, equal to that present in the nearby clouds at intermediate latitudes (Caraveo et al. 1981).

SAS-2 had discovered three localized γ-ray sources in the sky : the Crab and Vela pulsars, and a mysterious source named "Geminga" (Fichtel et al. 1975). (For present day γ-ray telescopes, a faint source whose angular extent is up to 2° may appear as a point source.) The COS-B workers searched systematically for sources with a Vela-like profile, standing above the background (Swanenburg et al. 1981 ; see also Bignami and Hermsen 1983). Of the new 22 sources isolated, only one is clearly identified to a point-like source : the quasar 3C273. Another source in the COS-B catalogue is in the direction of the ρ Oph dark cloud. It appeared to emit $\sim$ 5 times more γ rays than expected, given its estimated mass. This source has stirred much controversy, and stimulated a great deal of theoretical and observational work - some of it very fruitful -. It has been proposed that the ρ Oph cloud encompasses or is close to a source of c.r. ; these c.r. could be shock-accelerated (see next section) by winds from OB stars (Cassé and Paul, 1980) or by a nearby supernova (Morfill et al. 1981). Alternatively, ρ Oph could contain a compact γ-ray source. In an attempt to locate the hidden source, Montmerle et al. (1983) pointed the Einstein satellite in the direction of the core of ρ Oph ; they discovered an X-ray Christmas tree, thus showing that the atmospheres of T Tauri stars are the site of numerous energetic flares - a fascinating result, even though it may be irrelevant for the interpretation of the high-energy γ-ray data. In the mean time, more recent observations of the ρOph region by COS-B have led to a revised estimate of the γ-ray luminosity, which now exceeds the expected value by a factor of only $\sim$ 2. Also, this γ-ray source is about to lose its "localized source" status : it has now been resolved by COS-B, and the correlation between the CO map and the γ-ray map is quite good (Hermsen and Bloemen, 1983).

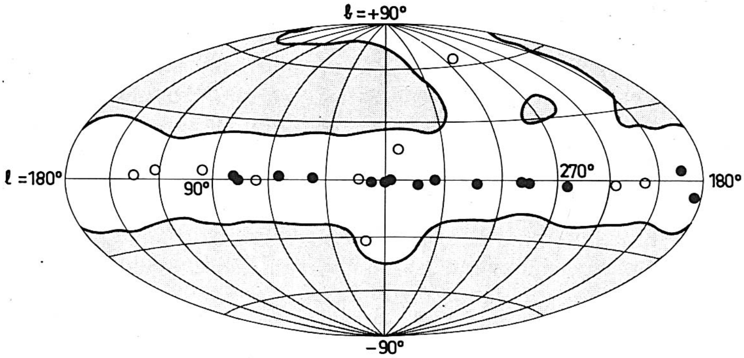

Figure 1 - Celestial distribution of the COS-B sources (Swanenburg et al. 1981). The closed circles denote sources with measured fluxes > 1.3×10^{-6} photons (>100 MeV) cm^{-2} s^{-1}; open circles denote sources below this threshold. Sources have been searched only in the unshaded area.

The remaining 21 γ-ray sources all lie at very low galactic latitudes (fig. 1). The fact that the latitude distribution is so narrow implies that they are concentrated along the galactic plane, and at distances from the sun much larger than their scale height ; this in turn suggests that they are associated to young galactic objects. Assuming a scale height H as small as that of the flattest (and youngest) galactic populations, H $\sim$ 40 pc, we find that the sources must be at least 2 kpc away. At the same time, the absence of a strong concentration of sources towards the Galactic Centre ($|\ell|<30°$) suggests that the observed sources are not too far either – probably not beyond 7 kpc from the sun. Their intrinsic luminosity, therefore, is in the range $0.4 - 5 \times 10^{35}$ ergs s^{-1}. A few of the COS-B sources may simply be a dense cloud or cloud complex, at intermediate distances ($\sim$1 kpc), traversed by a normal flux of c.r.

A class of objects which are young and tend to lie at low latitudes are the supernova remnants. These are either directly visible in optical light, or are detected through their radio-emission or X-ray emission. Their radio-spectrum is a power law, characteristic of synchrotron emission by a power-law spectrum of relativistic electrons. The energy density of relativistic particles in these objects is much higher than in the general interstellar medium, so that they are interesting candidates for gamma-ray sources. Given their linear sizes of $\sim$ a few pc, their angular size is generally small enough that they are point sources for the present gamma-ray telescopes. A few positional coïncidences between some of the first gamma-ray sources discovered and supernova remnants had been pointed out, early on ; at present, with the gamma-ray source error box covering over 10 % of the central regions for b<1°, while 125 supernova remnants are known, it seems evident that an undiscerning search for positional coïncidences cannot bring fruitful results.

Strong γ-ray emission may be expected if a supernova remnant bites on a dense molecular cloud ; this is most likely to happen in regions of star formation. A subclass of supernova remnants has been defined (Montmerle, 1979), singling out the objects in whose direction there is also observational evidence for star formation, such as the presence of associations of young stars (OB associations), or of hot gas ionized by them. Thirty two such objects, called SNOBs,have been listed, and 7 to 9 COS-B sources coïncide with them. Several other SNOBs are situated in more extended regions of intense gamma-ray emission. The γ-ray emission from SNOBs can be accounted for quantitatively by bremsstrahlung interactions of the low-energy tail of the electron spectrum revealed by the synchrotron emission, and cloud matter of density $\sim 10^2-10^3$ cm^{-3} (Montmerle and Cesarsky, 1980).

Apart from the two known young pulsars and the conventional sources obeying to the equation gas + c.r. = γ rays, is there a more exotic population of γ-ray sources ? Despite many efforts spent attempting identifications, we do not know yet. The best studied source is also the most tantalizing one : Geminga, the second brightest γ-ray source in the sky. The COS-B error box of Geminga, which is only a half square degree, has been explored at various wavelengths. The first searches yielded purely negative results : almost no gas, no bright X-ray source, or radio source, nothing ! But with deep searches, two possible candidates have appeared :
a) Moffat et al. (1983) have discovered several faint radio sources in the Geminga error box. One of them is optically identified to a quasar of redshift 1.2. The ratio L_γ/L_{radio} would then be $\sim 5.10^5$. For 3C273, the "typical" and only γ-ray quasar, this ratio is only ~ 100.
b) Bignami et al. (1983) found four X-ray sources in the Geminga error box. The brightest source, which has an a priori probability of a few % to be in the COS-B error box, seems a particularly good candidate. Because of the lack of absorption in the soft X-ray spectrum, it is probably nearby - not much beyond 100 pc. This peculiar X-ray source has an optical counterpart : a very faint blue object, such that $L_x/L_{opt} \sim 250$ (Caraveo et al. 1983). There is no radio source associated with it, and the X-ray emission does not appear to be variable on scales going from 2.6 msec to hours. If the identification is correct, Geminga has $L_\gamma/L_x \simeq 10^3$. There is at present no obvious explanation for this object.

Will the search for Geminga lead to the discovery of a new class of high-energy sources, and help to explain a sizeable fraction of the COS-B sources ? Difficult to predict ! The only established characterictic of the γ-ray sources is that they lie at low latitudes ; if Geminga is a quasar far away or a very nearby X-ray source, it is at low latitude just by accident !

COSMIC-RAY ACCELERATION BY INTERSTELLAR SHOCKS

Let us now return to the cosmic rays, which we had abandoned in our search for exotic γ-ray sources.Two ideas on the origin of c.r. have been in favour for much longer than I have been in the business : that cosmic rays are accelerated by the Fermi mechanism, and that their energy source is supernovae. Fermi (1949) introduced the idea that c.r. acquire their considerable energies by colliding a large number of times with magnetized clouds, gaining only a small amount of energy at each encounter.

One of the main reasons why this process has enjoyed such an endurable popularity among astrophysicists is that, under very simple conditions, it predicts that the energy spectrum of the colliding particles should be a power law, and power-law spectra are extremely frequent in non-thermal sources of radiation all over the universe. But the great drawback is that it cannot explain why the power law exponents of c.r. in the galaxy and in radio sources fall almost invariably in the range 2-3. A possible explanation of the spectral index and a link between cosmic-ray acceleration and supernovae has been established recently with the study of particle acceleration by diffusive shocks (Bobalsky, 1977, 1978).

Let us consider a strong shock, propagating at a velocity V in the direction of the magnetic field lines. We assume that $V \gg V_A$, where V_A is the Alfvèn velocity ($V_A{}^2 = B^2/4\pi\rho^*$, where ρ^* is the density of ionized particles). In the shock frame, the gas is flowing in at a velocity $u_1 = V$. At the shock, the gas is compressed by a factor r, so that the velocity downstream, relative to the shock, is $u_2 = V/r$. The presence of scattering centres of cosmic rays is postulated, so that cosmic rays diffuse on both sides of the shock. The scattering centres act as cosmic-ray traps, ensuring that the particles will be reflected back and forth across the shock a large number of times. Every passage through the shock is equivalent to running head-on into a "magnetic wall" of velocity $V=u_1-u_2=V(1-1/r)$. Thus, particles increase their energy by a small amount every time they cross the shock, as in a Fermi (first-order) mechanism. But here the average number of passages of the particles through the shock, before escaping downstream, is, like the energy gain per passage, completely determined by the shock characteristics. In the time-independent limit, this mechanism generates a power-law spectrum whose spectral index depends only on the compression ratio r of the shock, and not at all on the shock velocity, on the diffusion coefficient (assumed "small enough") or on the dimensions of the scattering region (assumed "large enough"). For strong adiabatic shocks, $r = 4$ and the differential spectrum of relativistic particles predicted is proportional to $1/(\text{energy})^2$.

The study of shock acceleration of cosmic rays is now an active area of research [See reviews by Axford (1981), Drury (1983)]. A detailed application of the simple mechanism I have just described to the acceleration of galactic cosmic rays by supernova shocks has been presented by Blandford and Ostriker (1980) [See also Moraal and Axford, 1983, Bogdan and Völk, 1983]. The mechanism has also been applied to terminal shocks from stellar winds, but not without controversy [see review by Cesarsky and Montmerle, 1983]. Let us now mention some of the problems encountered by the linear, time-independent theory just described :

a) If cosmic rays extract so much energy from the shock, their pressure can become the dominant one. For instance, this will inevitably occur if cosmic rays are getting accelerated by a strong shock, to a spectrum E^{-2} for a sufficiently long time. Even if the shock is not so strong ($r<4$), the cosmic ray pressure can become dominant if the rate of injection of particles in the system is sufficiently rapid. The expectation is that, eventually, the cosmic rays broaden the shock, making it a less efficient particle accelerator ; if the shock becomes wider than the particle mean free path λ, particles only get a small amount of adiabatic acceleration as they traverse the compressed regions, but a power-law tail does not develop. While some progress has been made (Eichler 1979, Ellison 1981), the full problem of non-linear shocks, as well as the distinct, but coupled problem of particle injection into the acceleration mechanism, still poses many intriguing puzzles.

b) This problem has always been treated in the framework of the quasi-linear theory, which assumes that the turbulent energy in the hydromagnetic waves acting as particle scatterers is much less than the energy density of the magnetic field. However, the anisotropies induced by supernova shocks in the pre-existing population of galactic cosmic rays are sufficient to render these waves extremely unstable; the wave amplitudes predicted by the quasi-linear theory are too high to be fully consistent with the theory. In addition, the waves play a role in the hydrodynamics and the thermodynamics of the system (McKenzie and Völk, 1982).

c) Finally, this acceleration process is slow ; consequently, when applied to realistic shocks, which have a finite lifetime, the theory predicts a high-energy cut-off. Under optimum conditions, the maximum energy that a proton interaction with a supernova shock can attain is 10^5 GeV ; under more realistic conditions, this upper limit can be as low as 2000 GeV (Lagage and Cesarsky 1983). In contrast, the observed spectrum of cosmic-ray protons is a power law up to 10^6 GeV (see review by Webber, 1983).

SUPERNOVAE AND THE INTERSTELLAR MEDIUM

In addition to their possible effect on the cosmic ray component, supernova (s.n.) shocks have a profound effect in shaping up the interstellar medium. Cox and Smith (1974) first pointed out that, given the high rate of s.n. explosions in the Galaxy, a part of the gas heated by a blast wave does not have time to cool down before it is hit again by a shock. Thus, at any time, a sizable fraction of the interstellar medium should be filled by hot ($T \gtrsim 5.10^5$ °K) and tenuous ($n \lesssim 10^{-2}$ cm^{-3}) gas. Global models of the interstellar medium have been proposed (McKee and Ostriker 1977, Cox 1981) ; but uncertainties on the distribution of cloud sizes, on the possibility of thermal and mechanical exchanges between clouds and the hot medium surrounding them, on the filling factor of a neutral, warm intercloud medium, and on several other variables make it impossible to devise a definitive model as yet.

The presence of hot gas in the solar environment has been confirmed by observations :

a) The Copernicus satellite detected absorption lines of O VI in the direction of several stars, indicating the presence of gas with $T \lesssim 5.10^5$ °K (Jenkins 1978a,b).

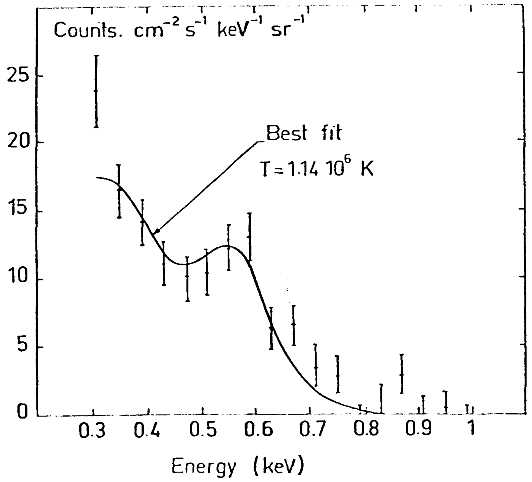

Figure 2 - Spectrum of the local hot bubble, obtained in the north galactic hemisphere with a solid-state detector Si(Li) with a large field of view (Rocchia et al. 1983). The feature around 550 eV is produced by the OVIII line emission. The large excess at low energies is attributed to a blend of CV and CVI lines. The solid curve is the expected spectrum of a thin plasma with T = 1.14×10^6 °K, in ionization equilibrium and with normal abundances.

b) Detailed maps of the soft X-ray sky in seven energy bands have been constructed over the last 7 years by the Wisconsin group (McCammon et al. 1983 and ref. therein). The interpretation of these data is far from straightforward : it is not easy to disentangle the relative positions of the hot gas, the cold clouds, the old s.n. remnants, the galactic halo. Still, a relatively isotropic, unabsorbed background of soft X rays seems to be present, which probably indicates that the solar system is embedded in a bubble of hot gas of radius 60 to 80 parsecs (Hayakawa et al. 1979), which is relatively empty of neutral gas. The thermal origin of this local X-ray emission has been confirmed by low-resolution spectra showing lines of stripped ions of iron, silicon, sulfur (Inoue et al. 1979) and carbon and oxygen (Rocchia et al. 1983, figure 2). If the elemental abundances are normal, the relative intensities of the lines are best understood if the gas is not in ionization equilibrium, which is what can be expected if a s.n. exploded nearby less than a few 10^5 years ago (Hayakawa et al. 1979, Cox and Anderson 1982, Arnaud et al. 1983).

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DISCUSSION

J.P. Ostriker: The Wisconsin Group argue that the soft-X-ray evidence implies that we live in a hot bubble. If the three-phase model of the interstellar medium is correct, then every observer will think he lives in a hot bubble: soft X-rays come from nearby, because of absorption by interstellar clouds, while hard X-rays can penetrate the clouds and thus come from larger distances. However the [OVI] lines observed by Copernicus cover a much wider range of space, and they are thought to come from the surroundings of clouds evaporating into a hot medium.

Another comment concerns the cosmic rays. The new fact in Hermsen's paper is the evidence for a variation of the electron/proton ratio with galactocentric distance. That reminds one of the following long-standing puzzle. The supernova remnants, though ideal candidates for supplying the galactic cosmic rays, cannot be the source locally because they contain predominantly electrons, while the local cosmic rays consist predominantly of protons. Perhaps the γ-ray observations can give us a handle on this puzzle.

Cesarsky: Yes - except that the variation in the e/p ratio indicated by the γ-ray studies is only a factor of 5, while the discrepancy between supernovae and cosmic rays is a factor of 100. So we are still a factor of 10 short. Also, the tracing of cosmic rays by γ-rays favours regions of high density, where protons may be trapped and generate secondary electrons. If dense clouds are more frequent at smaller galactocentric distances, this might already explain part of the factor 5.

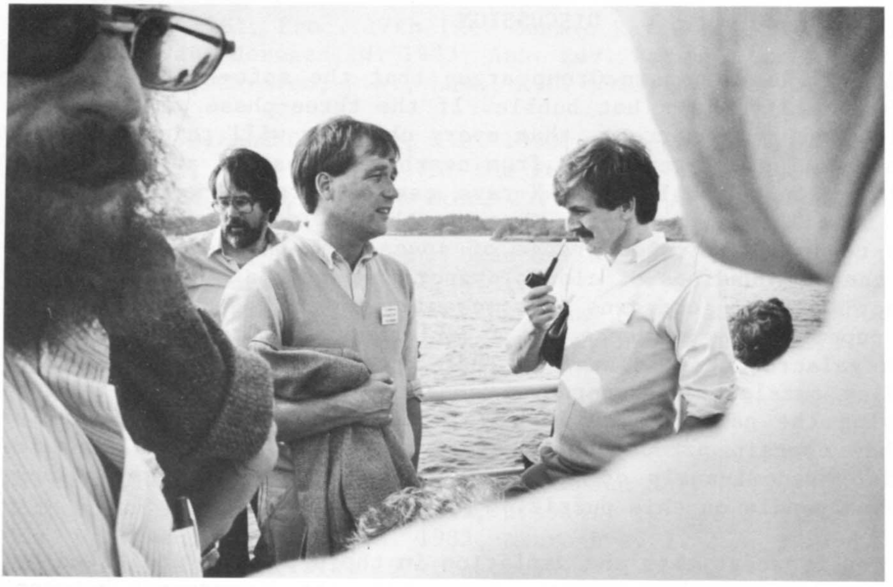
J.B.G.M. Bloemen: From the COS-B data, the radial gradient of the CR-electron density and the near-constancy of the CR-proton density (out to about 20 kpc) has sofar only been determined in the outer Galaxy. The analysis for the inner Galaxy remains to be done, but there are good indications that the results will be the same.

New COS-B observations of the ρ Oph complex show that the γ-ray source is extended along the two dust lanes.

J.V. Feitzinger to Hermsen: COS B has a very low angular resolution. This means that you run into problems of beam dilution at distances greater than about 5 kpc from the Sun. Can you comment on this problem?

W. Hermsen: At energies above 300 MeV, the resolution (FWHM) is ~1.5°. However, the angular response distribution is very sharp, also for lower gamma-ray energies for which the resolution is worse. The galactic large-scale structure is very different, in two dimensions, at small and at large distances from the Sun. Since the HI scale height is increasing with increasing distance in the outer Galaxy, the angular scales of structures at distances e.g. greater than 5 kpc from the Sun are still sufficiently large to be recognised in the gamma-ray distribution.

H.C. van de Hulst (Chairman): I am glad to hear that the COS-B quanta, which after all cost about a hundred dollars a piece, are paying off.



Wim Hermsen (left) and Hans Bloemen during boat-trip. Background: Jan Lub. Foreground: Harvey Liszt (left) and Hugo van Woerden discuss problems of mapping Our Galaxy's spiral structure. LZ

Below: Strong and Mayor discuss gamma-ray halo during poster session. CFD