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THE HIGH ENERGY GALAXY

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THE HIGH ENERGY GALAXY

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ABSTRACT

The galaxy is host to a wide variety of high energy events. I review here recent results on large scale galactic phenomena: cosmic-ray origin and confinement, the connexion to ultra high energy gamma-ray emission from X-ray binaries, gamma ray and synchrotron emission in interstellar space, galactic soft and hard X-ray emission.

1.INTRODUCTION

High energy phenomena are ubiquitous in the galaxy: cosmic rays pervade the interstellar medium and generate, through their interactions with magnetic fields, matter or light, radio synchrotron photons and gamma rays. X-ray radiation, most often of thermal origin, is emitted by a variety of sources: binary systems, pulsars, but also normal stars, and protostars. X-ray sources are particularly abundant in the region of the galactic center, which is also a source of gamma-ray line emission at 511 keV (electron-positron pair annihilation line), and perhaps also at 1.8 MeV (*radioactive decay of* ^{26}Al).

It is clearly impossible to summarize here all the recent achievements of high energy astrophysics in the galactic domain. Therefore, in the present review, I will restrict myself to large scale phenomena in relation to cosmic rays, X-rays and gamma rays.

I first summarize the status of cosmic-ray research, and in particular I dwell on some recent developments of the theory of cosmic-ray acceleration by *supernova shocks*. I also recall recent results on ultra high energy gamma-ray emission by some X-ray emitting binary systems, and discuss their interpretation in terms of acceleration at an accretion shock, and the possible connexion to the origin of high energy cosmic rays.

In the second part of this talk, I recall the representation of our galaxy derived from gamma-ray and radio continuum observations. I then turn to the integrated emission observed in the X-ray band: the soft X-ray emission, which may harbor a component originating in the galactic halo, and the hard X-ray ridge whose thermal nature has been demonstrated recently by the Japanese satellite TENMA.

2. GALACTIC COSMIC RAYS

2.1 Source spectral index: composition or anisotropy ?

After so many years of active research, there is not yet a firm answer to the question: where do cosmic rays come from ? The main problem is, of course, that the arrival direction brings little or no information on the source. Astrophysicists are then left with a less direct set of clues: spectrum, composition, energetics, anisotropy.

Observations must first be corrected for propagation effects; this is usually done in the framework of the galactic leaky-box model which assumes that cosmic rays are trapped between reflecting boundaries surrounding the galaxy, but with a finite probability of escape into extragalactic space. The cosmic-ray density is uniform throughout the confinement volume.

In the leaky box model, the only free parameter is the mean escape length λ_e (g/cm^2), which of course may be a function of energy. In most diffusion models, the elemental composition of cosmic rays is also determined almost exclusively by one parameter, le, which is inversely proportional to the diffusion coefficient (in one-dimensional models, or in three-dimensional models with scalar diffusion) or to the component of the diffusion tensor perpen dicular to the galactic plane. The constant of proportionality contains all the information on the distribution of the sources and on the boundaries of the containment region. Thus the "leaky box model" formalism can be used as a valid approximation if the propagation of cosmic rays in interstellar space is dominated by the diffusion process.

As cosmic-ray nuclei travel through interstellar space, they suffer inelastic collisions with interstellar medium nuclei; in this way "primary" cosmic-ray nuclei emitted by sources break up into lighter "secondary" nuclei. The escape length λ_e can be estimated by measuring the abundances of certain species expected to be absent in the primary spectrum.

In figure 1, we display the variations of λ_e with rigidity (R=pc/eZ, where p = momentum, c = velocity of light, e = electron charge, Z = nuclear charge), as derived from the data of the french-danish spectrometer C2 on board of HEAO 3 (Koch-Miramond et al. 1983). After accounting for solar modulation effects, these authors find: $\lambda_e = 22R^{-0.6}$ g/cm^2 of pure hydrogen.

Once λ_e has been calculated, the spectra of the primary species can be corrected for spallation and nuclear destruction effects.In this way, Engelmann et al. (1985) have derived source spectra of primary species with $Z > 5$ from HEAO3-C2 data. If H and He nuclei behave like the other species, to correct for propagation, the observed spectrum must be divided by $\lambda_e(R)$. The source spectra thus obtained are displayed in fig. 2. Data from other experiments are also represented. In the range $R \approx 2 - 200$ GV, Engelmann et al. (1985) find that, while the spectra of primaries with $Z \geq 5$ are similar power laws with index 2.4, the spectrum of protons appears to be flatter, with an index ≈ 2.1. (For He, the situation is somewhat confused, as can be seen on fig. 2).

The implications of this result, which is awaiting further confirmation, have not yet been studied in full detail. Essentially all of the published work on cosmic-ray origin continues to assume that protons and alpha particles originate and propagate as the other species, and that the λ_e derived from studies of heavy nuclei can be used to estimate the energetics. For the local kpsec^2 in the galactic plane, cosmic-ray energetics is derived using the fact that, on the average, cosmic rays escape at a rate $c\lambda_{gal}/\lambda_e$, where λ_{gal} is the column density of matter across the galactic disk. The energy requirement to maintain the cosmic-ray pool is then $\approx 10^{38}$ erg/Kpc^2 sec. (Alternative derivations, using also the cosmic-ray "age" derived from secondary radioactive isotopes, yield similar results). If we retain the same leaky-box model for all species, the results of Engelmann et al. (1985) imply that the local cosmic rays consist of two components: a flat component, with source index$\approx$ 2.1, and a steep component, with source index$\approx$ 2.7. At rigidities below $\approx$ 100 GV, most of the nuclei heavier than He would belong to the steep component, while at all energies the flat component would be dominant in the proton flux.

The leaky-box formalism, as we have seen, accounts well for the observations relating to the steep component which is rich in heavy nuclei.

But there is no compelling reason to believe that the flat component, which is relatively proton rich, has the same history. The steep component may be just local, and transient; the determinations of λ_e and of age from radioactive isotopes only relate to this component. But the proton rich component is the only one that counts when discussing energetics, constancy in time of the cosmic-ray flux, and isotropy, and the abundances of secondary elements with $Z>2$, at energies <100 GeV, may simply not be relevant when studying it!

Some light can be thrown on this problem by refining the spectra of hydrogen and helium, and studying carefully their secondaries ^{3}He, D and antiprotons.

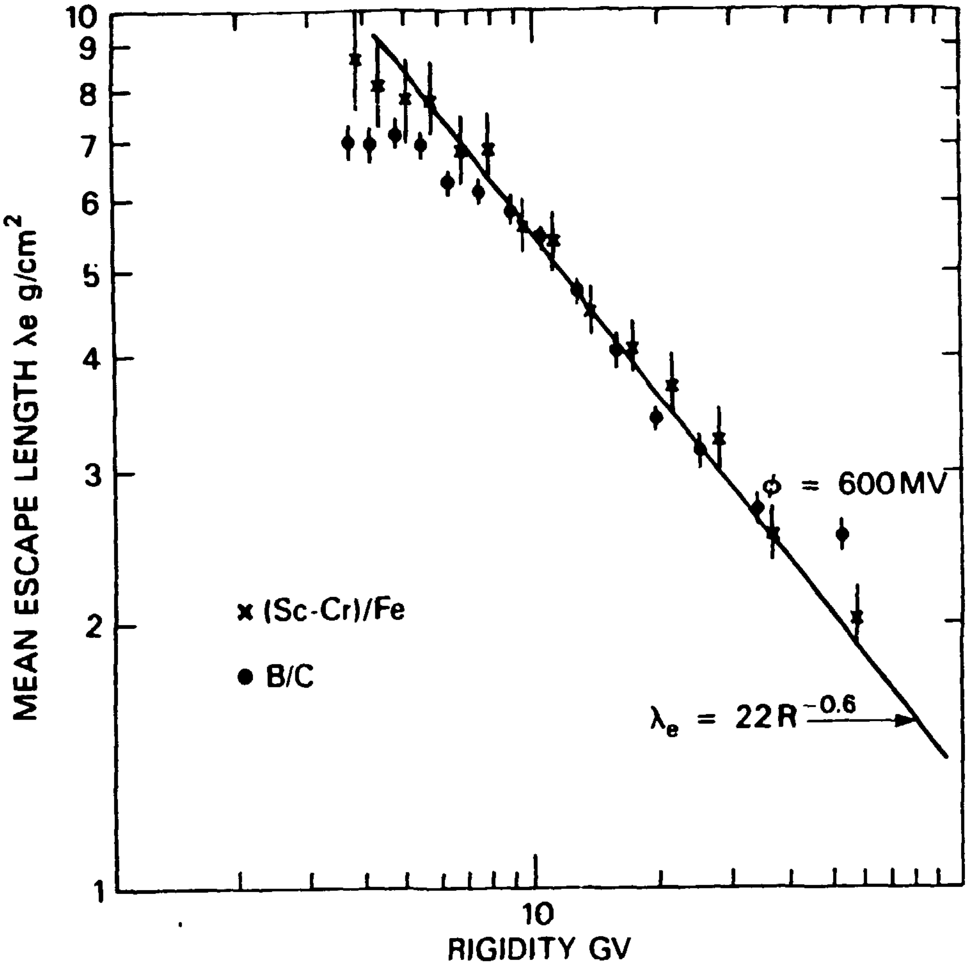

Figure 1. (from Koch-Miramond et al. 1983). Mean escape length as a function of rigidity for a modulation parameter ϕ.

2.2. Antiprotons

Secondary antiprotons are generated in the inelastic collisions between high-energy nuclear cosmic rays and interstellar medium particles. The flux of galactic antiprotons has been measured by Golden et al. (1984), by Bogomolov et al. (1979) and by Buffington et al. (1981) at various energies (fig. 3). The antiproton flux observed at 10 GeV is lower by a factor ≈ 6 than the prediction of the energy dependent leaky box model that accounts for the abundances of secondary nuclei such as Li,Be,B.

Buffington et al. (1981) measured the flux of cosmic-ray antiprotons in the range 130-320 MeV, corresponding after demodulation to a interstellar energy of ≈ 800 MeV. Their result, which has not yet received an independent confirmation, is more than an order of magnitude higher than predictions of the standard propagation models.

It may be that this unexpectedly high abundance of antiprotons is an additional indication that the history of all cosmic rays is not as deduced from the abundances of secondary nuclei alone. For instance, the high energy observations of antiprotons could be accounted for if all cosmic-ray protons had a source spectrum of index 2.1 and traversed 7.5 g/cm^2 in their sources before escaping into the galaxy, or if a fraction x of the cosmic rays traversed a slab of width X at the source with xX = 7.5 g/cm^2 (Lagage and Cesarsky 1985). As noted by these authors, a problem with this "thick-source" model is that, in addition to the antiprotons, neutral pions are produced, which decay into gamma rays. The total galactic gamma-ray flux predicted by this model exceeds that

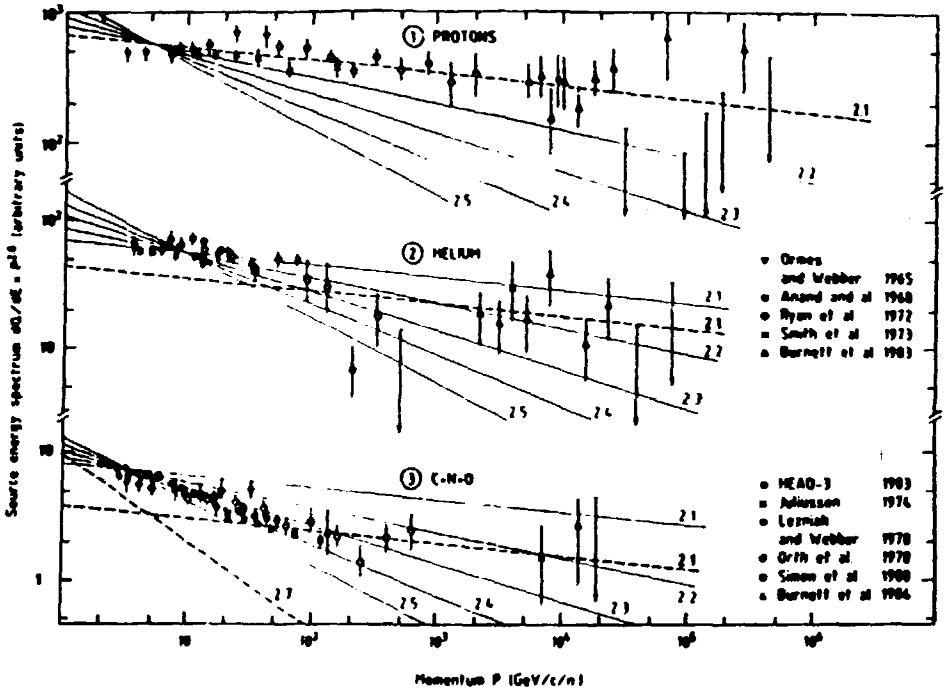

Figure 2. (from Engelmann et al. 1985). Differential source strength dQ/dE vs. momentum for (1) protons, (2) He, (3) CNO nuclei. The spectra have been flattened by multiplication by $P^{2.0}$, where $P = p/A$. The proton spectrum is well fitted by a power law with index 2.1. The dashed lines for He and CNO are an attempt to fit their high energy data with the same spectral index. In the case of CNO nuclei, a steep component of index ≈ 2.7 would have to be added to this main component.

observed by COS B by a factor ≈ 3. Alternatively, antiprotons may have a more exotic origin. They may be primary particles, e.g. originating in antimatter galaxies, (Stecker, Protheroe and Kazanas 1983) or from evaporating black holes (Kiraly et al. 1981); they may be produced by p–p collisions in relativistic plasmas (Dermer and Ramaty 1985), e.g. in the accretion shock surrounding a compact object; or by decay of photinos making up for the dark matter in the galactic halo (Silk and Srednicki 1984)...

A more complete set of observations of the spectrum of cosmic-ray antiprotons than presently available is required to further investigate these hypotheses. For lack of space, I do not discuss here the present results on D and ^{3}He, but I stress that, there too, additional observations would be very useful.

2.3. Anisotropy

An alternative point of view has been taken by Hillas (1984), who uses the anisotropy* as

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* Note however that part or all of this anisotropy may be due to high energy gamma rays, rather than to cosmic ray nuclei (Wdowczyk and Wolfendale, 1983; see also Watson 1985)

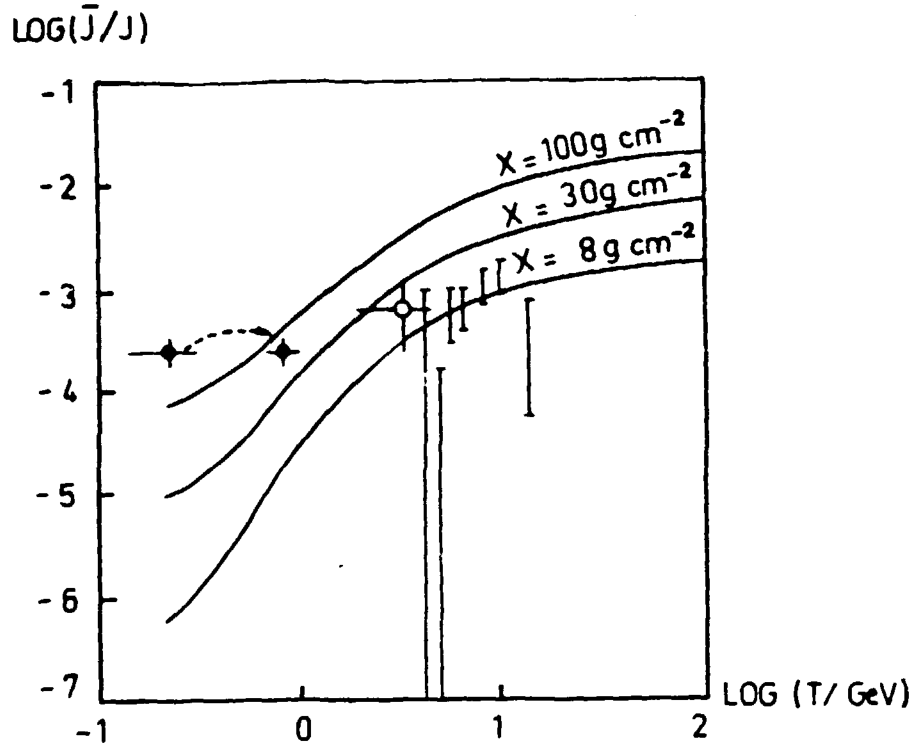

Figure 3. (from Lagage and Cesarsky 1985). Antiproton flux leaving thick sources with grammages 8, 30, 100 g cm^{-2}, compared with observations at different energies. Black dots, Buffington et al. (before and after modulation); white dots, Bogomolov et al., bars, Golden et al. The proton momentum spectrum taken is proportional to p$^{-2.1}$.

the main indicator on the propagation of galactic cosmic rays. This can only be done at energies $> 10^2, 10^3$ GeV, since at lower energies the trajectories of the cosmic rays are perturbed by the solar wind. Hillas notes that, at energies $> 10^3$ GeV, the amplitude of the first harmonic of the cosmic-ray anisotropy is, very roughly, proportional to the product (cosmic-ray differential flux × $E^{2.47}$) (fig. 4). Now, if r_c is the confinement time, the anisotropy is expected to be $\approx t/r_c$, where t is the time for escape in a straight line. Hillas proposes a simple interpretation of fig. 4: that the source spectrum is a power law of index 2.47 over the whole energy range, and that all the features in the spectrum are due to propagation effects. At 10^3 GeV, the amplitude of intensity variation is of $\approx$ 0.06%. If the boundary of the cosmic-ray confinement region is at h kpcs, $r_c(10^3 GeV) \approx 5h$ Myr. Since the spectrum of protons does not appear to change significantly between 5 and 10^3 GeV, the mean age at 5 GeV is then $\approx (1000/5)^{2.7-2.47} r_c(10^3\mathrm{GeV}) \approx 17h$ Myr (where 2.7 is the observed index of the proton spectrum at these energies). This is comparable to the age derived from radioactive secondary isotopes.

2.4. Cosmic-ray sources

In summary: what are the requirements on cosmic-ray sources ?

i) energetics: the order of magnitude of the power required to replenish every 20 million years cosmic rays within a cylinder of base 1 Kpc^2 within the galactic disk, of height 1 to several Kpc, is $\approx 10^{38}$ergs/sec.

ii) source spectrum: most probably a power law, at least in the range from a few GeV/n

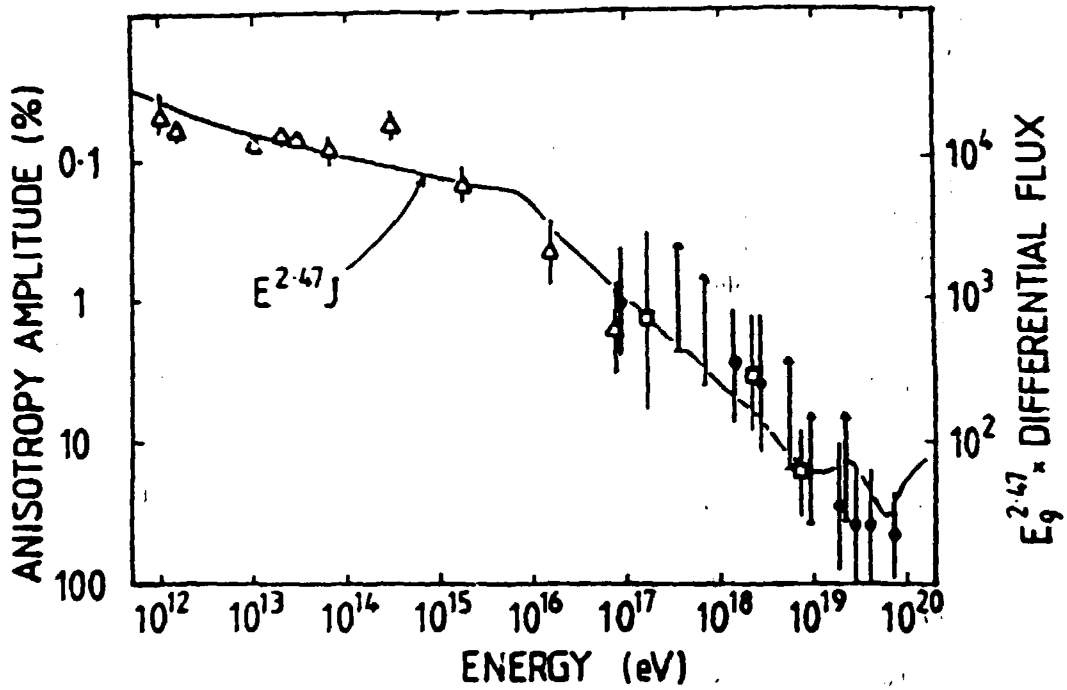

Figure 4. (from Hillas 1984). Amplitude of first harmonic as a measure of residence time: variation in anisotropy compared with variation in flux.

to≈ 10^6GeV/n, perhaps up to 10^8 or even 10^9 GeV! Spectral index: 2.1 ? 2.4 ? or 2.7 ? Or somewhere in this range.

iii) source composition: well determined now, for most elements, in the GeV range. May give clues to the origin of the cosmic radiation or at least, as we have seen, to a component of it.

Within a radius of 3Kpc from the sun, the average energy input from supernovae is estimated to be $\approx 10^{39}$erg $s^{-1}kpc^{-2}$; supernovae are widely believed to be the main accelerators of cosmic rays. Stellar winds expend $\approx 10^{38}$ erg $s^{-1}kpc^{-2}$ in the interstellar medium, and they may also contribute (Cesarsky and Montmerle 1983). Composition arguments have often been invoked to eliminate another likely candidate, from the energy budget standpoint : pulsars. But the debate on the role of pulsars in cosmic-ray acceleration is not closed (e.g. Ruderman 1985).

2.5. Diffusive shock acceleration

This attractive acceleration mechanism was introduced, almost a decade ago, and simultaneously, by several groups from all over the world (Krymsky 1977; Axford, Leer and Skadron 1977, Bell 1978, Blandford and Ostriker 1978). The basic ideas are:

i) every time a relativistic particle of energy E crosses a shock of velocity V, it suffers an energy increase $\Delta E \propto EV/c$.

ii) If particles can be retained for a long time in the shock vicinity by a scattering mechanism, they can cross the shock a large number of times, and their energy can be boosted by a large factor.

These aspects were not new, and had often been referred to in the literature as "first order Fermi mechanism". What was shown in 1977-78, for the first time, is that, under some general conditions (parallel or quasi parallel shock, i.e. where the magnetic field direction is not parallel to the plane of the shock; diffusion path length much longer than the width of the shock; shock velocity much higher than the Alfven velocity; test particle approximation for the cosmic rays; low level of the *magnetic turbulence* scattering the cosmic rays; strong, adiabatic shock; etc..) this process predicts, in the time independent case, a power law spectrum with $N(E) \propto E^{-2}$, and a somewhat steeper spectrum if the shock is not so *strong*.

The study of shock acceleration of cosmic rays is an active area of research. A fundamental review of the subject has been written by Drury (1983). A detailed application of the linear, time independent mechanism I have just described to the acceleration of galactic cosmic rays is given in Blandford and Ostriker (1980); see also Axford (1981).

Many aspects of this mechanism have been studied since, and it is impossible to review this rich field here. Let us just emphasize some of the main problem areas:

i) 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 this theory.

ii) 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 theshock is not so strong, 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, all particles of a given energy obtain the same amount of adiabatic acceleration as they cross the shock region.*

A complete, but approximate solution to the problem of cosmic-ray dominated shocks has been developed, over the years, by Ellison and Eichler (1985 and references therein). The main assumptions are:

- free injection of particles into the mechanism, from the thermal tail
- a *diffusion coefficient* which increases with the energy. As the shock is broadened by the effect of the cosmic rays, particles of different energy "see" a different shock strength; only the very high energy particles see the full shock.
- fast dissipation of the hydromagnetic waves by an undefined damping mechanism.
- particles of energy greater than some E_{max} are assumed to escape from the system.

This makes it possible to study the process in a time-independent fashion. But then the shock is no longer adiabatic; in principle the compression ratio can exceed its maximum adiabatic value (7 in this case, since for the cosmic-ray gas the adiabatic index is 4/3) and become arbitrarily large. Nevertheless, Ellison and Eichler find that this mechanism still produces a universal spectrum which is very similar to a power law of index ≈ 2. This is because the compression ratio is tempered by the fact that, upstream, the scattering centers of the cosmic rays are not attached to the fluid, but propagate with respect to it at the Alfven velocity. The efficiency of cosmic-ray acceleration by this mechanism is of 25 %.

iii) An important problem of the theories of shock wave acceleration is that the maximum *energy that can be attained is limited, either by the lifetime of the shock itself or by its curvature* radius. This problem was treated in detail by Lagage and Cesarsky (1983). In the case of supernova shocks, the limiting factor is the shock lifetime; under most optimistic assumptions, the maximum energy E_{max}, for particles of charge Z, is only $\approx 10^5 Z(B/10^{-6}G)$ GeV, where B is the strength of the magnetic field in the most *diffuse* phase of the *interstellar medium*.

This result holds whether the shock is linear or cosmic-ray dominated. Taking into account the non-linearity introduced by the fact that, upstream, the Alfven waves are generated by the cosmic rays, so that the diffusion coefficient is space and time dependent, limits E_{max} to values which may be as low as $2000Z(B/10^{-6}G)$ GeV. Invoking supernova shocks propagating in the galactic halo does not alleviate the problem.

The possible acceleration of high energy cosmic rays by stellar wind terminal shocks is still controversial. If shock acceleration is operating there over long times, stellar winds have the advantage that the shock is a standing shock, which remains strong for longer times than supernova shocks. The maximum energy is then determined by the shock curvature, and the strength of the magnetic field: $E_{max} \approx 5.10^5 Z(B/10^{-5}G)(D/5\ pc)$ GeV, where D is the shock radius.

If the galaxy emits a strong wind, cosmic-ray can be accelerated at the terminal shock at the boundary between this wind and intergalactic space. Jokipii and Morfill (1986) modelled this shock, and concluded that it could accelerate cosmic rays up to the highest energies observed. But particles of energy below $\approx 10^{15}$ eV are strongly modulated by the wind, and in most cases they do not reach the galactic plane; the shape of the spectrum when passing from supernova shock cosmic rays to particles accelerated at a hypothetical galactic wind shock is extremely model dependent.

3. VERY HIGH AND ULTRA HIGH ENERGY GAMMA-RAY EMISSION FROM X-RAY BINARIES.

Much excitement has been generated in the high energy community these last years over the detection of very high energy (TeV range) and ultra high energy (PeV range) gamma-ray emission from X-ray binaries. At such energies, the observations are made from ground, using the atmospheric Cerenkov technique for $10^{11} < E < 10^{13}$eV, and the air shower technique for $10^{14} < E < 10^{16}$eV. Detections have been claimed for five X-ray binaries: Cyg X3 and Her X1 in both domains, 4U0115+63 in the TeV domain and Vela X1 and LMC X4 in the PeV domain. In the ultra high energy domain, only Cyg X3 has been observed by several groups (Samorski and Stam 1983, Lloyd Evans et al. 1983, Alexeenko et al. 1985, Kifune et al. 1985), and this is one of the reasons why this source has attracted so much attention lately.

Cygnus X3 is a well known X-ray source. It was discovered by a rocket flight as early as 1966 (Giacconi et al. 1967). In the Uhuru and the Copernicus data, a periodicity of the signal was revealed, with a period which then seemed very short: 4.8 hours. Now, many X-ray sources are known which have similarly short periods.

In 1972, the source was observed to emit giant radio bursts, where its radio luminosity increased by a factor of several hundred. Since then, it has undergone violent outbursts about every thirteen months . Twenty-one cm. line absorption features in the spectrum allowed to establish a lower limit of 11.5 Kpc to the distance of this source. As to the gamma-ray emission:

- In the 100 MeV range, the SAS II team announced a positive detection. The Cos-B team, with much better statistics, but at a different epoch, only give an upper limit. Moreover, they questions the conclusion of the SAS 2 workers, and argue that Cyg X3 is not present in the SAS 2 data either (Hermsen et al. 1985).

- Over the least 14 years, several groups reported that they had detected Cyg X3 in the TeV or even in the PeV range. The signal generally covers a smal part of the phase period, and the various signals detected are not always in phase (Fig. 5). There have also been many non detections over the years. At this point, some authors question the statistical validity of the data (Chardin and Gerbier 1986), but most experts are convinced that the gamma-ray source, albeit fickle or at least sporadic, is indeed there (Watson 1985).

The uncertainty in the data at hand is too large to establish at present a firm estimate of the average gamma-ray luminosity of Cygnus X3. Values quoted in the literature are in the range $10^{36} - 10^{37}$ erg/s at TeV energies and several 10^{36} – 10^{37} erg/s at PeV energies, while the integral energy spectrum is reported to be a power law of index ≈ 1.1. In any case, the emission of TeV and PeV gamma rays from such sources indicate that they generate ultra high cosmic rays. As

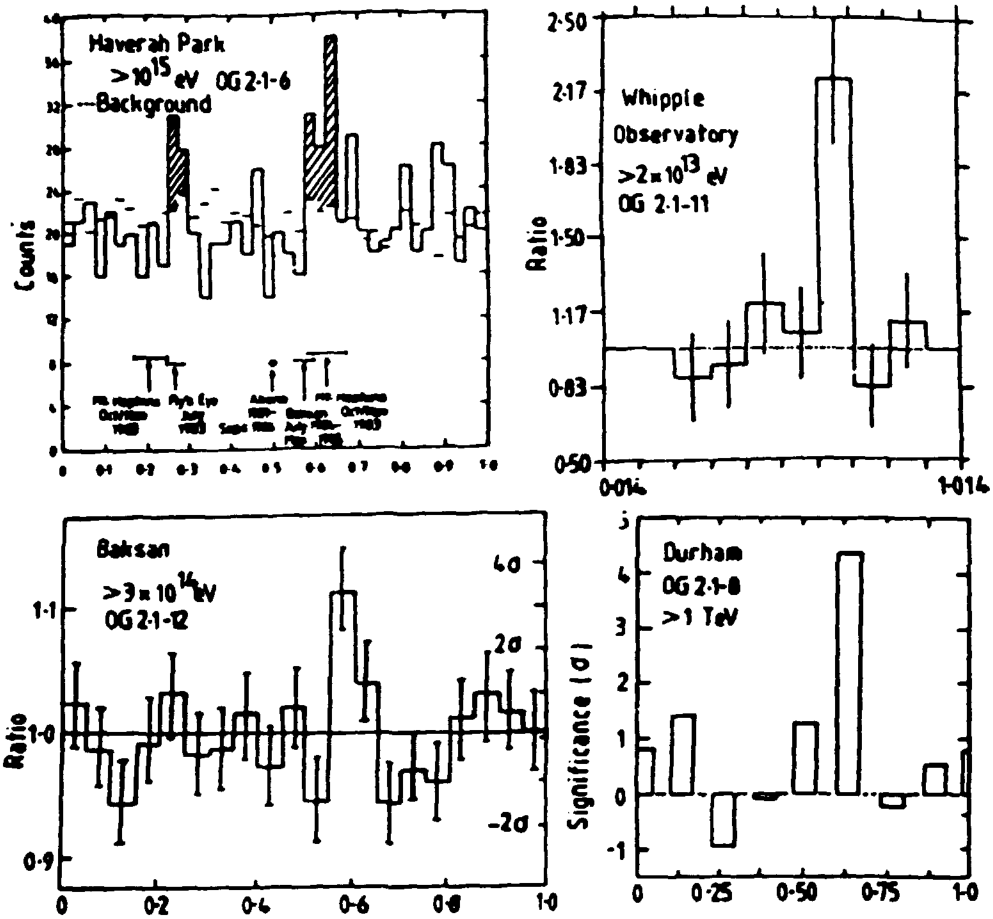

Figure 5. (from Watson 1985) Duty cycle of Cygnus X3 in high energy gamma rays.

we have seen, the acceleration of cosmic rays to energies in the PeV range or higher in our own galaxy is not a well understood phenomenon, and to identify with certainty at least some sources of these particles would fulfill the life dream of many a cosmic-ray physicist! It is therefore extremely important that these observations be repeated with more powerful installations, so that more than the tip of the iceberg can be uncovered.

High energy gamma rays emitted by X-ray binaries probably result from interactions of cosmic rays of even higher energy, accelerated at the source, with matter or with magnetic fields or radiation. At the same time, high energy gamma rays also interact with magnetic fields and with other photons to produce electron pairs. Consequently:

i) to obtain the production spectrum, the observed gamma ray flux must be corrected from the effect of absorption by source photons (Apparao 1984) and by photons from the microwave background or from stars, encountered while travelling from the source.

ii) The magnetic field strength B at the region of gamma ray production cannot be too intense For PeV gamma rays to emerge, B must be [illegible] 10^6 G (Stephens and Verma 1984). Now, very intense magnetic fields are required to accelerate cosmic rays to ultra-high energies in small sources. Therefore, it is likely that the cosmic rays and the gamma rays are not produced in the same region of the source.

To avoid this problem, and also to explain the doubly peaked light curve, with peaks at phase 0.2 and 0.8, which had been seen in early detections, Vestrand and Eichler (1982) proposed the "beam-dump" model. Cosmic rays are accelerated by a neutron star; the companion is surrounded by a dense atmosphere. Cosmic rays from the neutron star have to traverse part of this atmosphere to reach us; a cascade develops, with pions decaying into gamma rays or into electron-positron pairs which emit gamma rays by the bremsstrahlung process (and perhaps synchroton photons too, depending on the magnetic field). At phases greater than ≈ 0.2, but lower than ≈ 0.8, the neutron star is between the companion and the observer, which therefore does not receive gamma rays. At phases close to zero, the column of matter between the neutron star and the observer consists of too many radiation lengths, and the cosmic-ray source is obscured. Therefore it is only at phases ≈ 0.2 and 0.8 that a signal is received.

In some of the most recent observations (see fig. 5), the light curve shows a single peak, at phase ≈ 0.6. This could be understood if accretion of matter from one star to the other occurs via a stellar wind. Then an accretion cone forms around the neutron star, and the gamma rays result from interaction of cosmic rays with the matter in the cone (Hillas 1985)

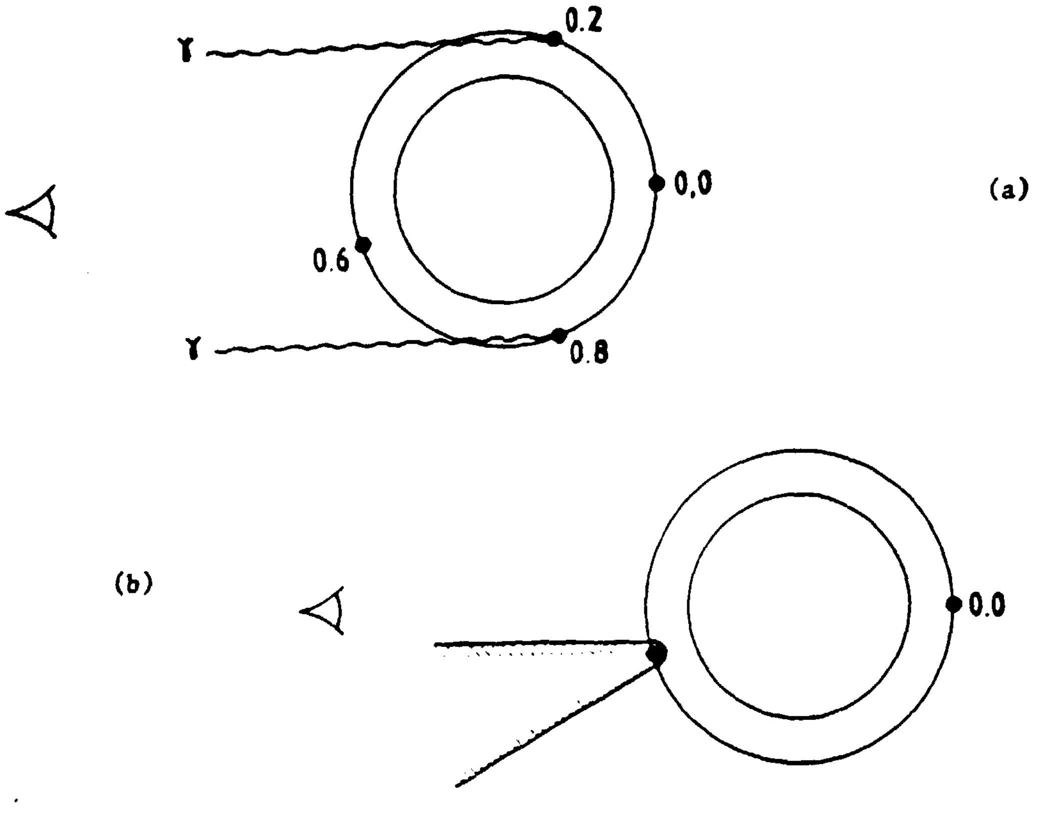

Figure 6. "Beam-dump" model for Cygnus X3. The phase is taken as equal to zero at the minimum of the X-ray light curve, when the compact object is completely occulted by its companion Gamma rays are produced by the interaction of cosmic rays emitted by the compact object with
a) gas from the extended atmosphere of the companion.
b) gas from the accretion cone in the wind of the companion.

What is more difficult to understand in this context is why the light curve appears sometimes to be single peaked, and sometimes to be double peaked.

Hillas (1984) has studied in more detail the development of an electromagnetic cascade induced by a monochromatic proton beam, at 10^{17} eV, traversing the shroud of matter surrounding the system. He has shown that the gamma-ray spectrum obtained fits the data at hand surprisingly well (fig. 7).

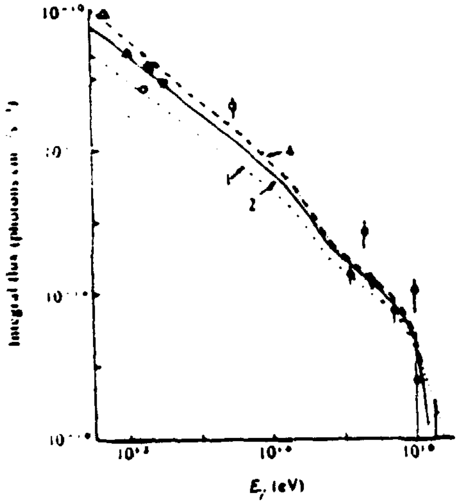

Figure 7. (from Hillas 1984) Calculated photon spectrum resulting from cascades initiated by 10^{17}eV protons in gas surrounding the companion star (magnetic field present), for cases where integration extends to maximum gas thickness 1, 2 and 4 Bremsstrahlung radiation lengths. Magnetic pair production causes the drop at 10^{16}eV. The dip starting at 10^{14}eV is due to pair production on primeval photons, assuming 12 kpc distance. The dotted line represents a non-magnetic cascade, initiated by 5×10^{16}eV protons (integrated to a maximum thickness of 16 radiation lengths).

(The particle beam does not have to be monoenergetic, as long as the energy carried by protons above 5×10^{16}eV is greater than that carried by protons in the four decades below).

This may solve the problem of the gamma-ray production, but only to shift the burden to another considerable problem: how can Cygnus X3 accelerate a powerful proton beam with E > 10^{17}eV ?

Hillas estimates the cosmic-ray production rate as given by:

$$2.10^{39}(\alpha/4\pi)(0.05/\Delta)(D/12\ \mathrm{Kpc})^2\ \mathrm{erg/s}$$

where α is the solid angle over which cosmic rays are emitted, Δ is the duty cycle in the light curve, and D the distance. Thus, if Cygnus X3 is an isotropic cosmic-ray source, it is emitting $\approx 10^{39}$ erg/s in cosmic rays at E $\approx 10^{17}$eV! Making reasonable guesses for the time of galactic confinement of cosmic rays of this energy, this is ≈ 20 times more than needed to replenish all the galactic cosmic rays in this range. In that case, we only need one source like Cygnus X3 once in a while in the galaxy to maintain the high energy cosmic ray pool.

Of the models proposed for Cyg X3, let us only mention that developed by Kazanas and Ellison (1986), which is another application of the diffusive shock acceleration mechanism. These authors propose that one of stars in Cyg X3 is in fact a black hole, surrounded by a spherical accretion shock. Then part of the ambient particles are accelerated, to a spectrum somewhat flatter than E^{-2}. The acceleration is only effective if, during this diffusive process, the energy gain due to the shock dominates over the loss mechanisms: photopion production, photodissociation, synchrotron losses, and, over all, inelastic collisions. The authors demonstrate that this is the case at energies $< 3.10^{16}$eV. But the main limitation to the maximum energy, as in the case of acceleration by stellar winds, is imposed by the geometry: the gyration radius of the accelerated particles cannot exceed $R_s u/c$, where R_s is the radius of the shock and u its velocity. This limits the energy to $E_{max} \approx 7.10^{15}(L_{38}/\beta)^{1/2}$eV, where L_{38} is the accretion power in units of 10^{38}erg/sec, and $\beta = 2u^2/v_A{}^2$ where v_A is the Alfven velocity. β must be $\gg 1$ for the mechanism to be operational. Thus the mechanism appears to fall short of $E_{max} \approx 10^{17}$eV.

4. GAMMA RAYS, RADIO CONTINUUM 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_o decay γ rays) and cosmic-ray electrons of energy > 30 MeV (bremstrahlung γ rays). There is also a small component due to the inverse Compton effect.

Figure 8. Galactic gamma-ray emission: the COS B survey.

In fig. 8, the Cos B gamma-ray map of the galaxy is displayed; the information contained there is supplemented by radio continuum studies. The Bonn map of the galaxy at 408 MHz is shown in figure 9. In the galactic disk, the similarity between these two maps is striking. An important difference is that the radio radiation has a much wider latitude distribution than the gamma rays; also, in the radio continuum map of figure 9, local supernova remnants, such as Loop I are very proeminent.

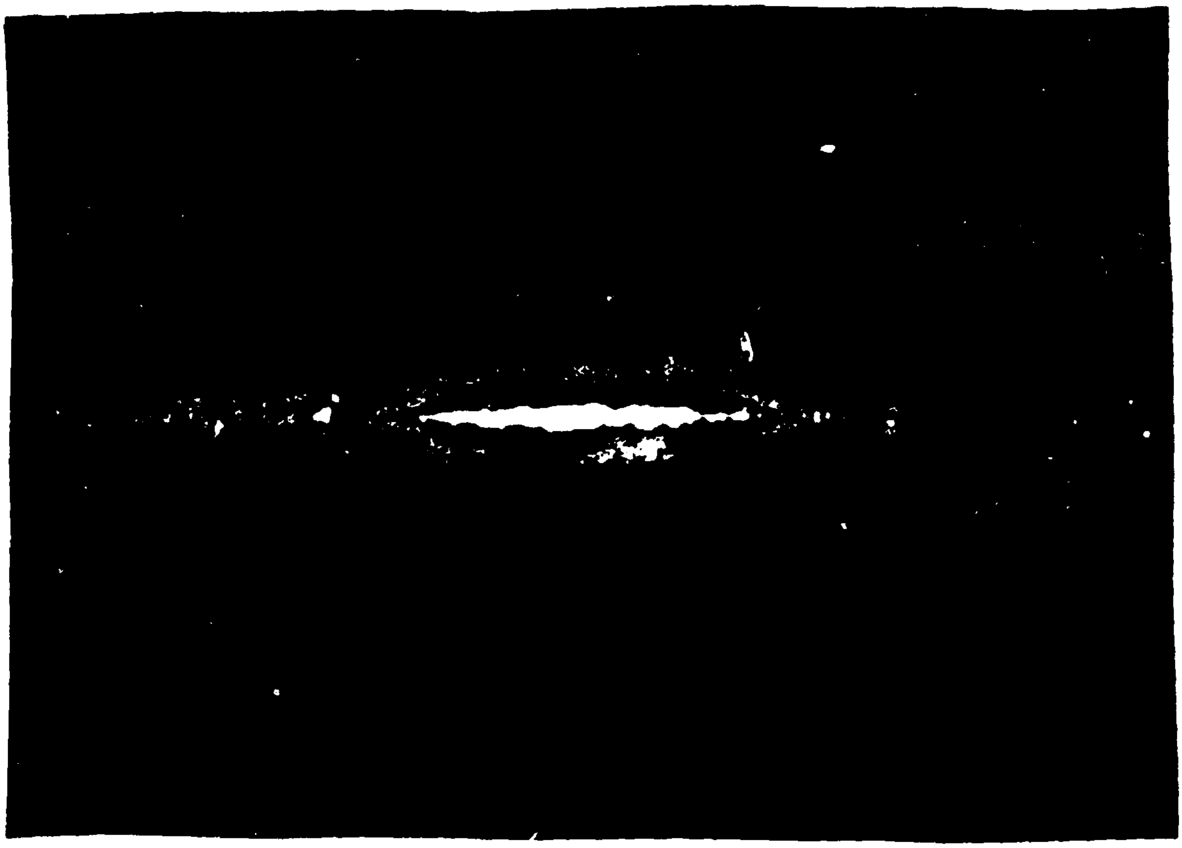

Figure 9. (from Haslam et al. 1982) Galactic radio continuum radiation at 408 MHz .

A simple conclusion is drawn right away: that the galactic magnetic field extends further away from the galactic plane than the gas. Consequently, for the past several years, the galactic continuum radiation has been modelled as a superposition of a thin disk, of equivalent width $\approx$ 250 pc in the inner galaxy, and a thick disk, $\approx$ ten times wider.

Another fact, known for a long time (Mills 1959) is that there are clear steps in the longitude distribution of radio-radiation, which are very well correlated to directions tangencial to spiral arms; these steps are also present in the gamma-ray galactic profile. This has led to a series of spiral models of the radio continuum background distribution in the galactic plane; the most recent one, based on the data of the Born survey, is shown in fig. 10 (Beuermann, Kanbach and Berkhuijsen 1985). Many similar gamma-ray galactic models have been proposed as well, starting with Bignami et al. (1975) and Paul, Cassé and Cesarsky (1976)

The gamma-ray emissivity per unit volume is proportional to the product of the densities of matter and cosmic rays, while that in radio synchrotron radiation is roughly proportional to cosmic-ray electron density $\times B^{1.8}$ The real hope, therefore, is to derive from the survey data the galactic distribution of gas, magnetic fields and cosmic rays.

But the variables in this problem are many: large scale ($\approx$ 1 kpc) and small scale ($\approx$ 10 pc) distributions of cosmic-ray nuclei, of cosmic-ray electrons,fraction of the observed radiation due to localized sources, also for radio radiation: separation into thermal and non thermal component, and for gamma rays : determination of the instrumental background. Of these, the distribution of atomic hydrogen and of thermal radio continuum can be determined in a reliable way from radio-

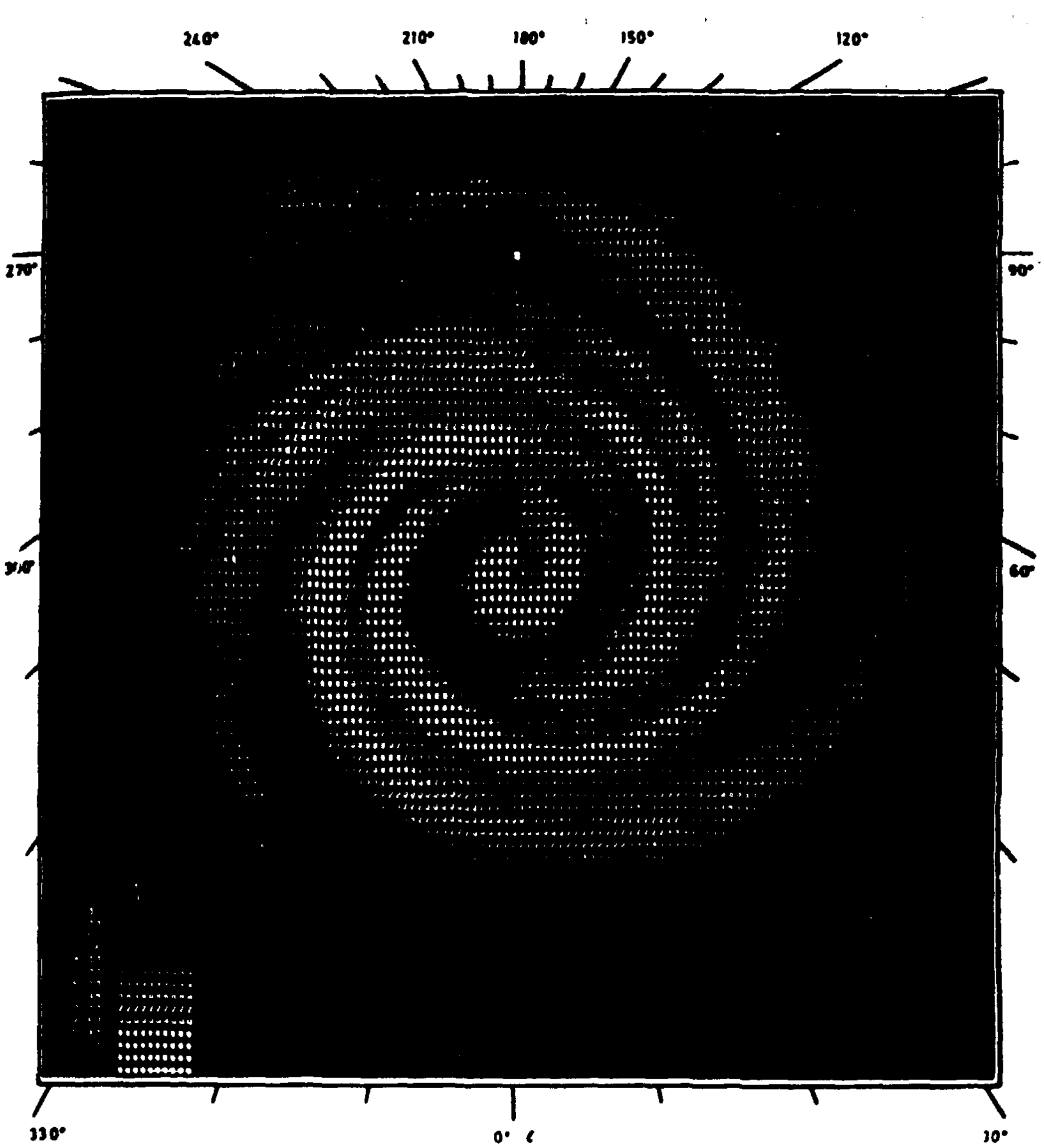

Figure 10. Distribution of the radio continuum emissivity in the thick disk of the galaxy; model by Beuermann et al. (1985). The sun and the galactic center are indicated by a filled symbol and a blank, respectively.

line observations. Estimates of the amount of molecular hydrogen are 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. Consequently, there is much controversy in the literature on this point.

Paul, Cassé and Cesarsky (1976) took a bold approach, and assumed that, everywhere in the galactic thin disk, the pressures of the gas, magnetic fields and cosmic rays are proportional to each other. Then, after selection of a spiral pattern, they could derive the distribution of the three components, from the radio and gamma-ray data. In this model, radial cosmic-ray gradients are present in the galaxy, with the cosmic-ray density peaking at the 5 Kpc ring. The distribution of cosmic-ray sources could also be derived, and turned out to be similar to that of supernovae.

In a subsequent paper (Cesarsky, Cassé, and Paul 1977) these authors compared the molecular hydrogen distribution predicted by their model to CO observations, and concluded that the conversion factor from CO emission to H_2 abundance depends on galactic radius, as expected from observations of abundance gradients in the galaxy. The galactic H_2 profile which they proposed encompassed much less H_2 than claimed by CO radioastronomers *. (Recently, Bhat, Mayer and Wolfendale (1985) arrived at a very similar galactic H_2 profile, invoking metallicity gradients and assuming from the start that cosmic-ray sources are distributed like supernovae).

In the mean time, the data base has been extended, and even more sophisticated methods of analysis have been applied. Now, with complete sky coverage in CO emission up to a latitude of at least ±10 deg the gas data can be directly compared to the gamma-ray data. The COS B group, in close association with the radioastronomy group at Columbia, have succeeded in establishing the excellent correspondence between gamma-ray and CO emission, region by region (Lebrun et al. 1983). It has become possible to go back to the COS B source catalogue, and eliminate the "point sources" which are simply clumps of gas pervaded by cosmic rays at a normal level (Pollock et al. 1985 and in preparation).

The cosmic-ray density in a nearby supernova remnant, Loop I, has been shown recently by several groups to be higher than elsewhere in the solar vicinity. This is a further indication that supernova remnants and cosmic rays sources are linked. (Bhat, Mayer and Wolfendale 1985, Lebrun and Paul 1985, Strong et al. 1985, Lebrun 1986).

Is there a galactocentric gradient of nuclear cosmic rays ? Many contradictory answers have been given to this question. The early work had led to a positive answer. Recently, the COS B workers adopted a pragmatic approach; they assumed that the gamma-ray emissivity per H atom is uniform at the kiloparsec scale, and is the same for HI and H_2, and used a maximum likelihood fit of the gamma-ray and radio line data to determine cosmic-ray galactocentric gradients in three energy intervals (70–150MeV; 150–300 MeV; 300–5000 MeV). They concluded that there is no need for a strong gradient in the CO/H_2 ratio, and that there indeed is a galactocentric gradient of gamma-ray emissivity per H atom, especially at low energies. They argued that it is only due to a gradient in the density of cosmic-ray electrons, while the cosmic-ray nuclei may be distributed uniformly in the disk out to at least 17 Kpc from the galactic center (Bloemen et al.1984, 1985). Several groups disagree with this conclusion (Bhat, Mayer and Wolfendale 1985, Harding and Stecker 1986), and the COS B group is refining further its analysis. In the meantime gamma-ray observations are not anymore standing rigidly in the way of the tenants of the universality of cosmic-ray nuclei.

5. X-RAY OBSERVATIONS AND HOT GAS IN THE GALAXY

5.1. Soft X rays: local bubble or halo ?

In addition to their possible effect on the cosmic-ray component, supernova shocks have a profound effect in shaping up the interstellar medium. Cox and Smith (1974) first pointed out that, given the high rate of supernova 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 sizeable fraction of the interstellar medium should be filled by hot ($T > 5.10^5$ K) and tenuous ($n < 10^{-2} \mathrm{cm}^{-3}$) gas. In the gravitational field of the galaxy, this gas has a scale height of several kiloparsecs, so that it extends to form a galactic halo or corona.

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

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* A detailed discussion on molecular hydrogen in the galaxy was presented at this meeting by P. Solomon.

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 definite model as yet.

A tantalizing question arises: can we obtain a general view of the hot interstellar medium, and perhaps even a peak at the halo, through soft X-ray observations of the sky ?

Complete maps of the soft X-ray sky in four soft X-ray energy bands have been constructed by the Wisconsin group (Mc Cammon et al. 1983 and ref. therein). The bands are denoted as: B(130–188 eV), C(160–284 eV), M1(440–930 eV), M2(600–1100 eV). These are supplemented by a partial survey in the Be band (80–110eV; Bloch et al. 1986), and by low resolution spectra in particular directions (Hayakawa et al. 1978, Inoue et al. 1979, Rocchia et al. 1984).

In the M band maps, again, the Loop I and North Polar Spur supernova remnants are very clearly visible; a few other features are present (Eridanus-Orion enhancement and Cygnus "superbubble"), and there is a very little additional structure.

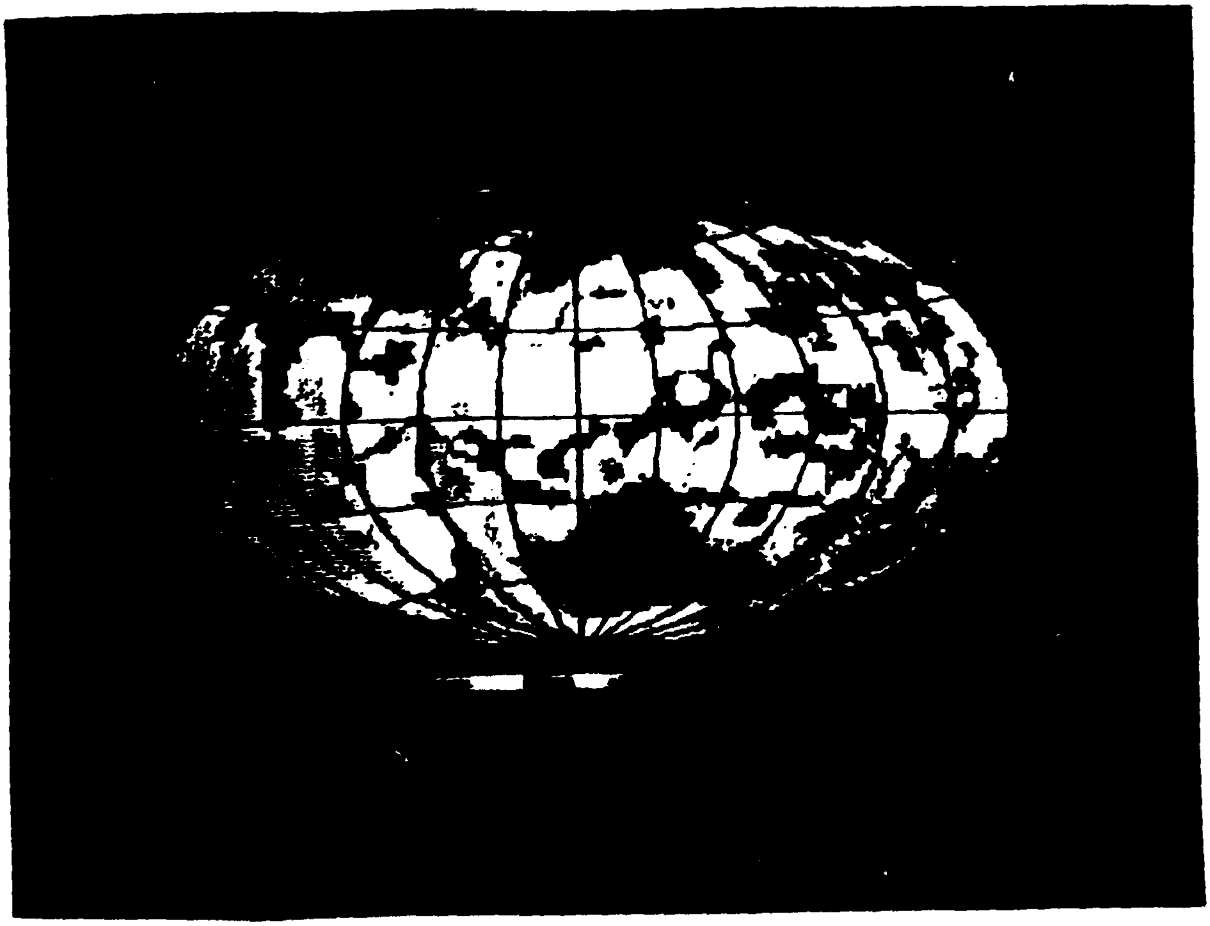

Figure 11. (from Mc Cammon et al. 1983) C band (160-284 eV) X-ray intensity map in galactic coordinates .

The B and C maps (fig. 11) are very different: prominent features are gone, and there is a distinctive brightening at the poles. That part of the X rays originate in nearby regions is evidenced by the considerable emission still present in the galactic plane. Still, there is a striking anticorrelation between HI column density and X-ray intensity; this suggests that part of the emission issues from regions at high galactic latitude, extending further away than the neutral gas which absorbs part of the radiation through the photoelectric effect.

This interpretation, however, encounters several problems. Among them, is the fact that the absorptions, in the B and C bands, which ought to differ by a factor two, are almost identical. Now Bowyer and Field (1969) and Bunner et al. (1969) had shown that the absorption cross section is diminished in an energy dependent way, if the clouds are distributed in small clumps, letting some of the X rays leak through them. Indeed, the halo interpretation of the B and C radiation holds if interstellar clouds are condensed into clumps of average thickness $\approx 2-3 \times 10^{20}\text{cm}^{-2}$. (Mc Cammon et al. 1983, Jacobsen and Kahn 1986); but it seems that the 21-cm data do not support quantitatively the clumping hypothesis (Jahoda, Mc Cammon and Dickey 1985), so that the X rays observed probably have a more local origin. In summary: we are sure that the solar system is embedded in hot gas, perhaps a hot bubble, but it is impossible to decide, from X-ray observations, whether this is a chance occurrence or a common place situation in the interstellar medium.

Recently, Arnaud and Rothenflug (1986) have modelled the local bubble, attempting to fit all the photometric and spectral data. They assumed spherical symmetry, and based their analysis on the Cox and Anderson (1982) study of a supernova expanding in a medium of constant pressure. They followed the time dependent ionization and recombination of the various species. Their best fit (see fig. 12) is for a supernova that exploded 10^5 years ago, so that the gas in the bubble has now a temperature of 1.1×10^6K; it is noteworthy that some depletion of heavy elements into grains is required to account for the data.

5.2. Hard X-rays: the galactic ridge.

The existence of an X-ray (2-10 KeV) galactic ridge has been suspected since the early observations by Cooke, Griffiths and Pounds (1969). HEAO 1 confirmed the existence of this ridge (Worrall et al. 1982), which was later mapped by Exosat (Warwick et al. 1985, fig. 13). The X-ray "ridge" is in fact a disk of radius 10 to 12 Kpc, and a height of a few hundred parsecs. The total luminosity of the ridge is 10^{38}erg/sec.

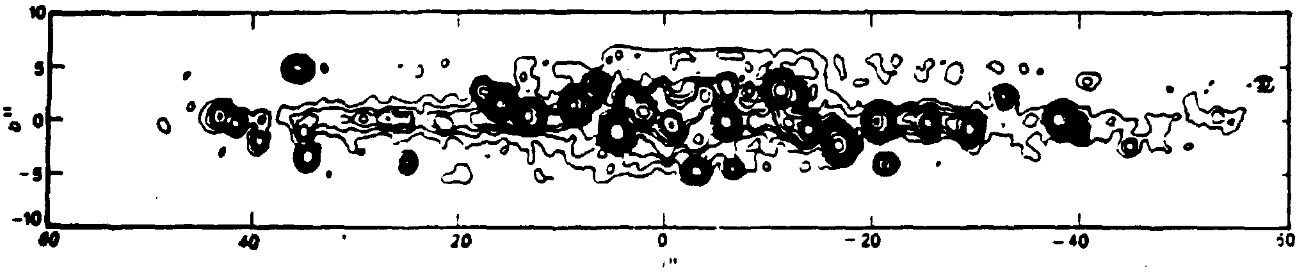

Figure 13. (from Warwick et al. 1985) Contour may of the 2-6 keV X-ray galactic ridge obtained with Exosat.

Until recently, the radiation from the galactic ridge was believed by some to be of non-thermal origin; e.g. synchrotron radiation of cosmic-ray electrons of energy $\approx 10^{14}$eV in the galactic magnetic field (Bhat et al. 1986).

But in 1986, Koyama et al published spectra of the galactic ridge, taken at different points in the galactic plane. The spectra have a characteristic thermal shape, and in most spectra the helium like iron line is present at 6.71 ± 0.04 keV, at about the expected intensity for a normal Fe abundance. The temperatures derived from the spectra are in the 5-10 keV range.

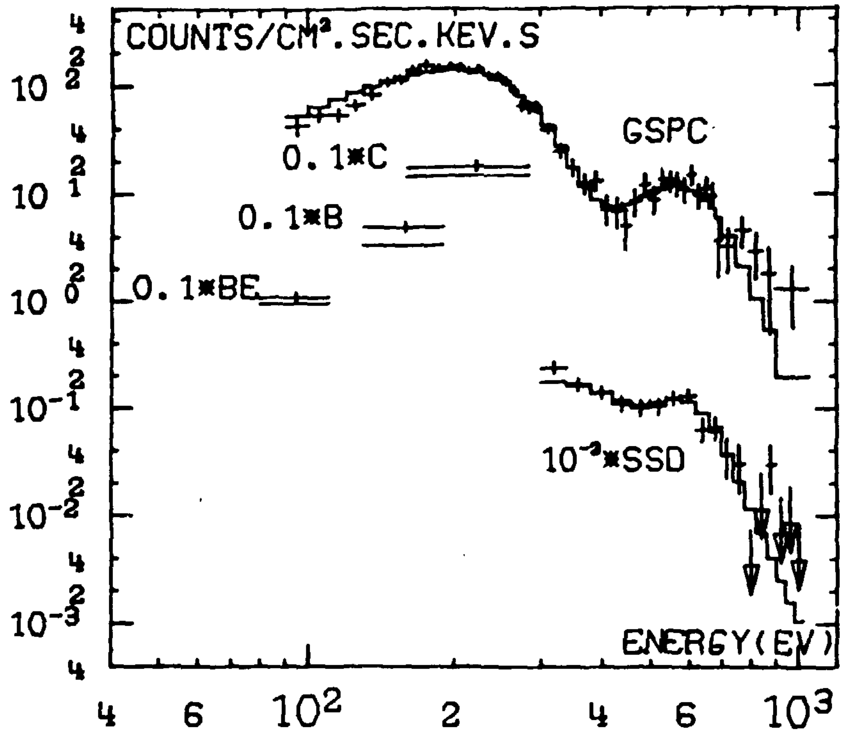

Figure 12. (from Arnaud and Rothenflug 1986) Fit of the photometric and spectroscopic data on galactic soft X-ray emission, with a local bubble model.

Koyama et al. argue that the radiation from the galactic ridge is due to young supernovae, less than 10^4 years old, of individual luminosity $\approx 10^{35}$erg/sec in the 2-10 keV range. The gas emitting the X rays would have a density ≈ 0.1 cm^{-3}; these objects would be too faint to be detected by the Einstein satellite. The rate of supernova events required in the galaxy is then of 1 supernova every 10 years, which seems high. An additional problem with this interpretation is that, in young supernovae, ionization equilibrium is not established, and the iron line at the observed temperatures would be shifted to 6.6 keV.

It is not clear yet whether it will be possible to explain the ridge as a superposition of small sources, or whether it has revealed the existence of a new, and probably transient, very hot phase in the interstellar medium.

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