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GAMMA RADIATION ASSOCIATED TO STELLAR FORMATION IN THE GALAXY

(COSMIC RAY ASTRONOMY)

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Résumé: Rayonnement gamma associé à la formation d'étoiles dans la galaxie.
(Astronomie du rayonnement cosmique)

Le ciel gamma dévoilé par le satellite COS-B est très particulier: quelques "étoiles gamma" se détachent sur une voie lactée brillante.

Nous montrons qu'une manière d'interpréter ce ciel est d'invoquer l'existence de régions dans lesquelles les étoiles, les rayons cosmiques et la matière interstellaire coexistent sous des formes très concentrées. Un lien génétique est établi entre nuage, étoiles et rayonnement cosmique: une partie de la masse du nuage se fragmente en étoiles, les étoiles les plus massives accélèrent le rayonnement cosmique sous l'effet des vents supersoniques qu'elles dispensent, le rayonnement cosmique interagit à son tour avec ce qu'il reste de nuage pour produire en abondance des rayons gamma de haute énergie: une source γ est née.

Abstract:

The gamma ray sky revealed by the COS-B satellite is very peculiar: a few "gamma ray stars" lying along the galactic plane emerge from a bright milky way. A possible interpretation of this sky is to invoke the existence of regions in which stars, cosmic rays and interstellar matter are very concentrated. A genetic link is established between clouds, stars and cosmic rays: the partial fragmentation of a cloud give birth to stars, the most massive stars accelerate cosmic rays through their supersonic stellar winds, cosmic ray interact in turn with the cloud material to copiously produce high energy gamma rays: a gamma ray source is born.

I - INTRODUCTION

The acceleration sites of galactic cosmic ray nuclei (the so called cosmic ray sources) remain mysterious. From the analysis of the cosmic ray composition in the GeV - 100 GeV range it has not been possible to define their nature, their number, neither their distribution (see e.g. Cassé (1979) for a review).Fortunately the recent discovery of gamma ray sources held out the possibility of identifying at least some of the cosmic ray sources. The reason being that high energy gamma rays ($E \gtrsim 100$ MeV) originate in the interaction of cosmic rays with the inert galactic gas* and so can be used to determine strong concentrations of particles if the distribution of target matter is known.

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* In the following we made the implicit assumption that most of the gamma ray sources are not associated to pulsars since i) only 2 pulsars (Crab and Vela) are known to be strong gamma rays emittors and ii) the latitude distribution of gamma ray sources is much narrower than that of pulsars. However, very young pulsars (Panagia and Zamorani 1979)black holes or another kind of compact objects cannot be excluded as source candidates.

II - GAMMA RAY SOURCES

The gamma ray sky survey made by the European COS-B satellite (Mayer-Hasselwander et al.1980, Wills et al.1980) following the American SAS II satellite (Fichtel et al.1975) has revealed 29 hot spots (Fig.1) emerging from a strong galactic background whose intensity declines from the central part to the edges of the galaxy.

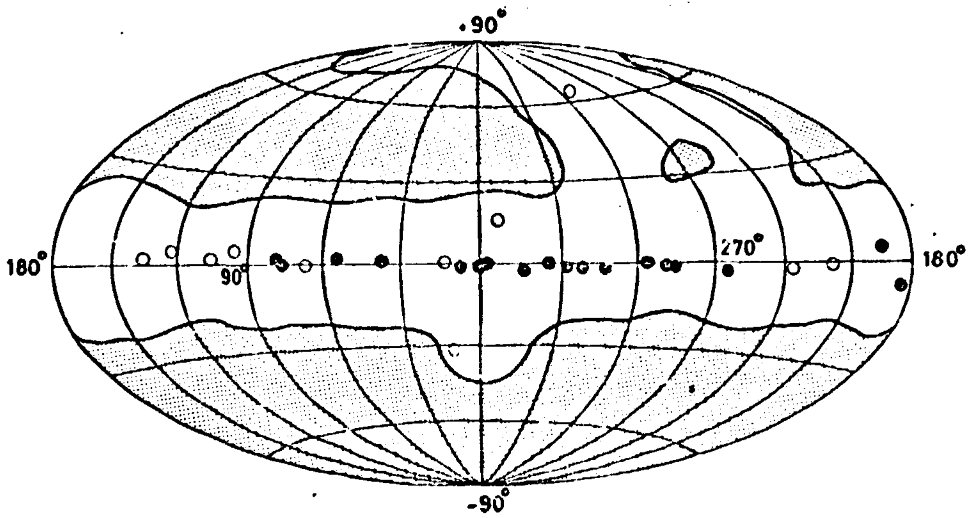

Fig.1 - Region of the sky searched for gamma-ray sources (unshaded) and sources detected above 100 MeV by spatial analysis. The closed circles denote sources with measured fluxes $\geqslant 1.3 \times 10^{-6}$ photon $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Open circles denote sources below this threshold (Wills et al.1980).

It is necessary to state clearly that gamma ray telescopes, like COS-B, have a very poor resolution power by astronomical standards. The resolution power is limited by the intrinsic angular resolution of the instrument (a few degrees at 100 MeV) and by background problems. A so call gamma ray source is operationnally defined as a localized enhancement on the 2-dimensional (l, b) sky map, compatible with a standard source profile (namely the profile of the stronger point source: the Vela pulsar).

The position of a discrete source cannot be appreciated with a precision better than 1 or 2° depending on the source intensity and spectrum relative to the surrounding background. Then, observationnally speaking no difference exists between compact sources (except for pulsars for which the temporal signature is unambiguous) and relatively extended sources (angular diameter of up to $\simeq 2°$). Moreover, in the inner galaxy ($-30° \lesssim l \lesssim +30°$) sources are less contrasted, therefore more difficult to isolate, then, the sample is not free from selection effects.

The energy spectrum of a given source will depend on the physical conditions prevailing at the source (matter density, CR proton density and spectrum, CR electron density and spectrum, photon field) through the respective contributions of the different gamma ray production mechanisms ($\pi°$ decay, electron bremsstrahlung, Compton scattering). Unfortunately the lack of precise energy spectra of point-like sources do not allow to determine the main emission mechanism in each individual case.

With all these limitations in mind we will try to enlight the astrophysical significance of this new class of galactic objects. Among the 29 discrete gamma-ray sources detected by the COS-B satellite (Wills et al.1980), only 2 have been identified with certainty: the Crab and Vela pulsars. Probable identifications include the Rho Oph dark cloud (Simpson 1979, Cassé and Paul 1980, Bignami and Morfill 1980) and the quasar 3C273 (Swanenburg et al.1980, Pollock et al.1980). 13 (or maybe 17) of the remaining 25 sources have been accounted for by Montmerle (1979a,b) in terms of SNOB's (supernova remnants physically linked with OB associations). Other identifications have been proposed for some specific sources (see Montmerle 1979a and reference therein), but the SNOB model is presently the most general. In this model low energy particles (1-10 MeV/n) copiously injected by active stars pertaining to an OB association are accelerated by the shock induced by a supernova remnant (SNR) expanding within the association. This injection-acceleration mechanism meets the physical constraints imposed by the cosmic ray source composition (Cassé and Goret 1978, Cassé 1979). Since acceleration by shock waves induced by SNR has been discussed in details in the literature (see e.g. Blandford and Ostriker 1978, Blandford 1979) and seems to have found with the SNOB model a propicious astrophysical framework, we focus, in the following, on a distinct process in which the energization of CR is assumed by supersonic stellar winds.

III - COSMIC RAY ACCELERATION BY SUPERSONIC STELLAR WINDS

Supernovae or their remnants (SNR's, pulsars) play, according to the general belief an overwhelming role in the acceleration of the cosmic radiation (see e.g.Ginzburg and Sirovatsky 1964).This conviction is mainly based on energetic arguments and on the observation of a strong radio synchrotron emission indicating the presence of a large concentration of non thermal electrons in young SNR. It seems timely to question this exclusive view.

It has been recently recognized that supersonic stellar winds (SSSW's) from massive stars (of the OB or WR type) are so powerful that they must strongly perturbate their environment, producing hot bubbles around these stars which are very similar in structure to SNR's (see e.g. Conti and Mc Cray 1980 for a review). It would be surprising that the dynamical effects of SSSW's were restricted to local interstellar heating and ionization. If we believe that SNR's energize CR particles via dissipation of kinetic energy (through e.g. a shock wave) it seems intuitively natural that SSSW's play a comparable role since i) SSSW's and expanding SN shells are both highly supersonic and ii) the total mechanical energy output integrated over the lifetime of OB stars are comparable to the mechanical energy carried by SNR's. Replace SNR by SSSW and electrons by protons (synchrotron radiation by gamma radiation), you will get the basis of the wind acceleration model proposed by Cassé and Paul (1980) together with its observational conterpart. In this model SSSW's from massive stars carry magnetic irregularities that Fermi-accelerate protons and nuclei to relativistic energies. The acceleration takes place at the boundary between the stellar wind and the surrounding medium. Provided particles are sufficiently confined to this region, they cross the discontinuity many times and get many energy increments until they leave the acceleration region. This recycling process leads naturally to a power low energy spectrum, the spectral index depending ultimately on a free parameter: the diffusion mean free path close to the discontinuity.

IV - GAMMA RAY EMISSION FROM STAR FORMATION REGIONS

Rho Oph is *the closest* aggregate of gas, dust and young stars (distance $\simeq$ 160 pc) and Carina (distance $\simeq$ 2.7 kpc) comprises *the richest* concentration of young and massive stars (OB and WR stars) known in the galaxy as well as the extraordinary ηCar object. Both are gamma ray source candidate.

a) Gamma ray emission of the Rho Oph cloud

The dense part of the cloud which contains most of the mass (2000 to 4000 $M_\odot$) lie within the error circle of the source discovered by COS-B at l = 353°, b = 16° (Hermsen 1978, Wills 1980). The observed flux (1.1 10^{-6} photons above 100 MeV cm^{-2} s^{-1}) is 4 to 10 times higher than if, within the cloud, the CR intensity and energy spectrum were such as observed in the solar vicinity (Simpson 1979, Cassé and Paul 1980, Bignami and Morfill 1980). As i) no other source candidate (e.g. SNR, radio pulsars, strong X ray source) has been detected in this direction and ii) the uncertainty on the cloud mass is not sufficient to explain the discrepancy, the natural interpretation of the observational material is that relativistic particles are *accelerated* and *confined* within the Rho Oph cloud, increasing locally the CR density. In the absence of SNR in the cloud and its vicinity (Apparao, Hayakawa and Hearn 1979) we have proposed that the acceleration is the result of the SSSW mechanism, the trapping being due to self-confinement of CR by Alfen waves they generate in the surrounding interstellar medium (Cassé and Paul 1980). The low CR electron density indicated by the lack of observed synchrotron emission from the Rho Oph cloud imply that the bulk of the gamma ray emission arises from proton-induced π^0 decay. The power injected in the form of CR required to sustain the gamma ray luminosity is of the order of 6 10^{33} ergs^{-1}. According to the criterium established by Snow and Morton (1976), none of the B stars embedded in the cloud is expected to have a strong SSSW, but the B1 III star HD 147 165 (σ Sco) about 5 pc away is expected to release $\simeq$ 10^{36} ergs^{-1} in the form of stellar wind. This amount would be sufficient to consider the wind from σ Sco as the main accelerating agent, but recent Copernicus measurements (Snow 1980, private communication) tend to show that the mass loss rate of this star is actually much less than predicted on the basis of its spectral type. However, the contribution of T-Tauri stars, embedded in the cloud may in fact account for a substancial release of mechanical energy (Paul, Cassé and Montmerle in preparation). Any firm conclusion would be premature due to considerable uncertainties on the parameters of the mass outflow of T-Tauri stars.

b) Gamma ray emission of the Carina nebula (Montmerle,Cassé and Paul, in prep.)

The gamma ray source at $l = 288^\circ$, $b = 0^\circ$ may be associated with the Carina complex which comprises several OB associations and Wolf-Rayet stars as well as the extraordinary η Car object and possibly a SNR. The eventual presence of this SNR makes the situation confusing since the gamma ray flux can be accounted for solely by the SNOB model (via either bremsstrahlung or π^0 decay), or by supersonic wind from O and WR stars, or even from η Car itself (via π^0 decay). In this case the total kinetic power in the form of SSSW is 2 to 6 10^{38} ergs s^{-1}[*] (up to 2.10^{40} erg s^{-1} if η Car is included). If the interpretation of the gamma ray flux from the Carina complex in terms of π^0 decay induced by CR injected in the placental molecular coud is correct a high density of relativistic particles (10 to 100 times the one measured in the earth vicinity) must exist implying a high trapping efficiency ($\gtrsim$ 50%) and hence an efficient conversion of CR energy into gamma ray energy. In this case a modest acceleration efficiency (conversion of the mechanical energy injected by SSSW into CR energy) is required ($\simeq 10^{-4}$ to 10^{-2}).

We have examined whether other OB associations are detectable high energy gamma ray sources, owing to the interaction of accelerated particles with the dense molecular clouds still present around young and massive stars. The 3 factors that govern the gamma-ray "visibility" of a given OB association are i) the rate of kinetic energy released in the form of SSSW depending on the number and on the type of mass losing stars, ii) the angular extent of the association and iii) the distance of the OB association. We found that the presence of Wolf Rayet stars bring a dominant contribution to the mechanical energy injected. Comparing the relative detectability of the 72 OB associations listed by Humphreys (1978), supplemented by a number of newly discovered ones we conclude that the gamma ray flux from a few associations (as Cyg OB2, Sco OB1) should be comparable to that of the Carina complex, unfortunately these are

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[*] Based on empirical laws derived from recently published bolometric corrections , mass loss rates and terminal velocities.

located in confuse regions of the gamma ray sky and are difficult to separate from the background. Most of the remaining OB associations must be undetectable as individual gamma ray source by the COS-B satellite but they must contribute significantly to the diffuse galactic background.

Although compatible with many observations the SSSW acceleration model is still seeking for firm observational supports. On the theoretical point of view one of the most questionable point of the model is the CR confinement in dense clouds.

V - POSSIBLE CONSEQUENCES ON THE ORIGIN OF LOCAL COSMIC RAYS

a) Possible acceleration sites in the local environment: the luminous stars in the Gould Belt

Most of the nearest OB stars, young clusters and stellar associations as well as dark clouds are concentrated in an expanding ring: the Gould Belt. A compilation of the stellar catalogs reveals the existence of at least 44 OB stars with $M_b \lesssim -6$ within 500 pc of the Gould Belt center ($l = 180°$, $b \approx 16°$, distance = 212 pc). Among these 44 stars, 18 have been observed by the Copernicus satellite, and 17 show evidence for mass loss. The estimated mechanical power supplied by these 44 stars alone ($\simeq 2.10^{38}$ erg s^{-1}) already exceeds by a factor of $\simeq$ 5 the power required to sustain the local CR density in a sphere of $\simeq$ 1 kpc diameter during $\simeq 2.10^7$ yr, the adopted CR confinement time (Garcia-Munoz, Mason and Simpson 1977). The most massive stars ($\gtrsim 20\ M_\odot$) born in the Gould Belt have disappeared since the bulk of star formation took place some $1.2\ 10^7$ years ago (Blaauw 1972). They may, however, have accelerated CR still present today in the solar vicinity. They may altogether have released 3.10^{54} ergs in the form of SSSW* i.e. more than 100 times the energy required to maintain the CR energy density in a sphere of 1 kpc diameter during 2.10^7 yr. Then assuming that the confinement volume of the local CR is not severely underestimated, a moderate conversion efficiency of stellar wind energy into particle energy is sufficient to account for the observed CR energy density.

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* This is a lower limit since WR stars have not been included neither pre main sequence mass-losing stars.

b) Wolf Rayet stars and the origin of the ^{22}Ne excess in cosmic rays

Since wind acceleration is not supposed to accelerate thermal particles* , a continuous injection of low energy particles ($E \simeq 1$ to 10 MeV/n) is required. We keep open the possibility that these particles are injected from the interior of the stellar cavity, i.e. by the mass losing star itself by a flare-like surface activity for instance. Observations or even indications of flare activity on hot and massive stars are mandatory to settle this idea. In this context, we expect that the CR reservoir is the surface of young and active stars and that the difference between the cosmic ray source (CRS) composition (corrected for propagation effects in the interstellar medium - ISM) and the surface composition of young stars (reflecting for most of them the present and local ISM) is principally due to selective effects at injection depending on the atomic properties of the elements. This idea is supported by 3 arguments (Cassé and Goret 1978, Cassé 1979, Meyer, Cassé and Reeves,1979) i) the general resemblance between solar cosmic ray elemental abundances and elemental CRS abundances (see e.g. Mewalt 1980) and ii) the correlation between the(cosmic ray source/local galactic) abundance ratio and the first ionization potential and iii) the fact that dust grains must have been thoroughly destroyed in the medium from which cosmic ray are extracted. In the interstallar gas in which dust grains are present, Ni, Fe, Mg and especially Ca and Al are highly depleted (Spitzer and Jenkins 1976, Salpeter, 1977) whereas they are normally abundant in CR.

The selective acceleration effects including a more subtle mass effect (Meyer, Cassé and Reeves 1979) do not significantly alter the <u>isotopic</u> proportions of any given heavy element at the CR source. The isotopic composition is, therefore, the most genuine print of the thermonuclear origin of CR. The isotopic analysis of CR is still in its adolescence and definite conclusions must await for the results of the third HEAO satellite. At the present time, with our limited observations it seems that the isotopic CR composition inferred at the CR source is not strongly abnormal for the principal elements between H and Ni (see e.g. Stone 1973, Meyer 1975, Waddington 1977, Balasuhbrahmanyan 1979) <u>except for Ne</u>. The ^{22}Ne/^{20}Ne ratio estimated at the CR source is thought to be about 3 times larger than the solar system isotopic ratio (see e.g. Balasuhbrahmanyan 1979 and references therein). We are inclined to relate this

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* A lower energy threshold is imposed by the fact that the energy increment between 2 shock crossings exceeds the energy ionization losses (see Cassé and Paul 1980 for details).

pecularity to the fact that Wolf-Rayet stars of the WC type, whose surface abundances are expected to be enriched in helium burning products - and especially in ^{22}Ne - could contribute significatly to the CR injection and acceleration (Cassé, Paul and Meyer, in preparation). The role of WR stars in the CR energization has been illustrated in section 4b. ^{22}Ne is believed to be the product of ^{14}N-burning through the sequence $^{14}N\ (\alpha,\gamma)\ ^{18}F\ (e^{+}\nu)\ ^{18}O\ (\alpha,\gamma)\ ^{22}Ne$. This chain of reactions starts before the 3α reaction (He-burning) and ends in the core of massive stars at the end of He-burning by $^{22}Ne(\alpha,n)\ ^{25}Mg$. Since according to stellar models the helium core is never in contact with the external convective envelope in normal (H-rich) stars (see e.g. Iben 1977) or even pure Helium stars (see e.g. Stother and Chin 1977), the only way to get ^{22}Ne at the stellar surface is to remove the envelope and expose the convective core. It seems to be the case for massive helium stars (WC stars) resulting from Roche lobe overflow in close binary systems followed by stellar wind mass loss (De Loore, De Grève and Vanbeveren, 1978, Vanbeveren and De Grève 1978, Vanbeveren and Packet 1979). Assuming that every atom of CNO initially present in the volume occuped by the helium convective core has been converted into ^{14}N and subsequently into ^{22}Ne, the ^{22}Ne excess would be at the surface of a typical WC star of the order of 130 (relative to solar system). Since the ^{22}Ne excess inferred at the CR source is about 3 the contribution of WC stars has to be at maximum 3/130, neglecting other possible sources CR ^{22}Ne as e.g. explosive hydrogen burning (Cassé, Meyer and Reeves 1979, Audouze, Chièze and Viangioni-Flam 1980). The dilution, in the proportion ≃ 1/40 of the ^{22}Ne-rich component with the bulk of CR expected to be of normal composition would lower the He and C (and/or O) excesses of the extra-component to a level compatible with the CRS abundances. Lower mass helium rich stars like nuclei of planetary nebula are presently under study.

VI - CONCLUSION

If confirmed these idea could perhaps be taken as the very beginning of a new yield in cosmic physics, that one might call "cosmic ray astronomy".

This work has been made in collaboration with Jacques Paul, Thierry Montmerle and Jean-Paul Meyer.

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* The Ne elemental excess will not appear in the spectra of WC stars because Ne lines are not observable in the visible and UV ranges.

REFERENCES

Apparao,K.M.V., Hayakawa,S. and Hearn,D.R. 1979, Ap.Space Sci.,65,419

Audouze,J.,Chièze,J.P. and Viangioni-Flam,E. 1980, Astro.& Astrophys. (in press)

Balasuhbrahmanyan 1979, 16th Int.Cosmic Ray Conf.,Kyoto,rapporteur paper

Blaauw,A. 1972, in Stellar Ages,ed.G.Cayrel de Strobel and A.M.Delplace (Meudon: Paris Observatory), Chapter 22

Bignami,G.F. and Morfill,G.E.,1980, Astron.& Astrophys.,(in press)

Blandford,R.D. 1979, in Particle Acceleration Mechanism in Astrophysics, La Jolla Institute,ed.J.Arons,C.Max and C.McKee (New York:Am.Inst.of Physics),p.333

Blandford,R.D. and Ostriker,J.P. 1978, Ap.J.Letters,221,L29

Cassé,M. 1979 in Particle Acceleration Mechanism in Astrophysics,La Jolla Inst., ed.J.Arons,C.Max and C.McKee (New York:Am.Inst.of Physics),p.211

Cassé M. and Goret,P. 1978, Ap.J.,221,703

Cassé M.,Meyer,J.P. and Reeves,H. 1979, 16th Int.Cosmic Ray Conf.,Kyoto

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

Conti,P.S. and Mc Cray,R., 1980, Science 208,9

Garcia-Munoz,M.,Mason G.H. and Simpson,J.A. 1977, Ap.J.,217,859

Fichtel,C.E.,Harman,R.C.,Kniffen,D.A.,Thompson,D.J.,Bignami,G.F.,Ogelman,H.B., Ozel,M.E. and Tümer,T. 1975, Ap.J.,198,163

Ginzburg,V.L. and Sirovatsky,S.I. 1964 in Origin of Cosmic Rays,Pergamon Press

Hermsen,W. 1980, Ph.D.Thesis, University of Leiden

Humphreys,R.H. 1978, Ap.J.Suppl.,38,309

Iben,I. 1977, in Advanced Stages of Stellar Evolution, 7th Advanced Course Swiss Society of Astronomy and Astrophysics (Saas-Fee)

de Loore,C., De Grève,J.P. and Vanbeveren,D. 1978, Astron.& Astrophys.,67,373

Mayer-Hasselwander,H.A., Bennet,K., Bignami,G.F., Buccheri,R., D'Amico,N., Hermsen,W., Kambach,G.,Lebrun,F., Lichti,G.G.,Masnou,J.L.,Paul,J.A., Pinkau,K.,Scarsi,L.,Swanenburg,B.N. and Wills,R.D. 1980, Proc.9th Texas Sympo. Ann.N.Y.Acad.Sci. 336,211

Meyer,J.P. 1975, 14th Int. Cosmic Ray Conf.,Munich,rapporteur paper,11,3698

Meyer,J.P.,Cassé,M. and Reeves,H., 1979, Proc.16th Inter.Cosmic Ray Conf.,Kyoto

Mewalt,R.A. 1980 (preprint)

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

Montmerle,T. 1979b, Proc.16th Inter.Cosmic Ray Conf.,Kyoto,OG-1,185

Panagia,N. and Zamorani,G. 1979, Astron.& Astrophys.,75,303

Pollock,A.M.T., Bignami,G.F., Hermsen,W., Kambach,G.,Lichti,G.G.,Masnou,J.L., Swanenburg,B.N. and Wills, R.D. 1980 (preprint)

Salpeter,E.E., 1977, Ann.Rev.Astr.Ap., 16, 267

Simpson,G. 1979, in Particle Acceleration Mechanism in Astrophysics, La Jolla Institute,ed.J.Arons,C.Max and C.McKee (New York:Am.Inst.of Physics),p.289

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

Spitzer,L. and Jenkins,B. 1976, Ann.Rev.Astr.Ap., 15, 133

Stone,E.C. 1973, 13th Inter.Cosmic Ray Conf., Denver, rapporteur paper 5,3615

Stothers,R. and Chin,C.W. 1977, Ap.J., 216,61

Swanenburg,B.N., Bennet,K., Bignami,G.F., Caraveo,P., Hermsen,W., Kambach,G. Masnou,J.L., Mayer-Hasselwander,H.A., Paul,J.A., Sacco,B., Scarsi,L. and Wills,R.D., Nature, 275, 298

Vanbeveren,D. and De Grève,J.P., 1979, Astron.& Astrophys.,77,295

Vanbeveren,D. and Packet,W., 1979, Astron.& Astrophys.,80, 242

Waddington,C.J., 1977, 15th Inter.Cosmic Ray Conf.,Plovdiv, rapporteur paper

Wills,R.D. 1980, in Non Solar Gamma Rays (COSPAR),ed.R.Cowsik and R.D.Wills, Pergamon Press, Oxford and New York, p.159

Wills, R.D., Bennet,K., Bignami,G.F., Bucchieri,R.,Caraveao,P., D'Amico,N. Hermsen,W., Kambach,G., Lichti,G.G., Masnou,J.L., Mayer-Hasselwander,H.A., Paul,J.A., Sacco,B. and Swanenburg,B.N. 1980, in Non Solar Gamma Rays (COSPAR), ed.R.Cowsik and R.D.Wills, Pergamon Press, Oxford and New York,p.43