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Gamma-Rays from Cosmic-Ray Irradiated Molecular Clouds

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Gamma-rays from cosmic-ray irradiated molecular clouds

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1. Introduction

An examination is made of the contribution to the number of apparently discrete sources of γ-rays from cosmic rays interacting with molecular clouds in the Galaxy. Attention is directed to specific nearby clouds and to clouds in general, the latter by a Monte-Carlo analysis.

2. Specific molecular clouds

Of the nearby molecular clouds the dark cloud near ρ-Ophiuchus (ρ-Oph) should be a good candidate for study. It has been detected by γ-rays in the COS-B experiment (Wills *et al.* 1980; $I_\gamma\,(>100\text{ MeV}) \approx 1.1\times10^{-6}\text{ cm}^{-2}\text{ s}^{-1}$) but not by SAS-2 (Fichtel *et al.* 1975; $I_\gamma\,(>100\text{ MeV}) < 1.5\times10^{-6}\text{ cm}^{-2}\text{ s}^{-1}$ at the 95% level). We have recently claimed (Issa *et al.* 1980) that there is rough consistency between the observed flux (averaged between the two experiments) and that expected on the basis of a cosmic-ray flux close to that observed locally interacting with the gas in the cloud ($F \approx 1$). However, other workers do not agree (Morfill *et al.* 1980; Paul *et al.* 1980; Cassé & Paul 1980); they adopt a smaller mass than that used by us and thus need a higher cosmic-ray flux ($F > 1$).

In defence of the conservative view (i.e. $F \approx 1$) we argue as follows. The mass of neutral gas within some 5 pc of the 'centre' of the complex appears to be *ca.* $6\times10^3\ M_\odot$; to this must be added a contribution of *ca.* 20% for ionized gas (Baart *et al.* 1980; Jenkins 1976), giving about $7.2\times10^3\ M_\odot$. The corresponding γ-ray flux above 100 MeV at the Earth will be about $0.8\times10^{-6}\text{ cm}^{-2}\text{ s}^{-1}$ for an adopted distance of 160 pc. Our weighted observed flux was $0.7\times10^{-6}\text{ cm}^{-2}\text{ s}^{-1}$ and there is thus no discrepancy. Comparison with the COS-B value alone ($1.1\times10^{-6}\text{ cm}^{-2}\text{ s}^{-1}$) does not reveal a significant discrepancy either. The adopted mass may have been over-estimated, of course, but it should be remarked that it is possible that the adopted distance is too great (Gurzadyan 1980) and there is thus the possibility of compensation.

An examination can be made of the rival treatments, which require $F > 1$. The strongest arguments can be made against the idea of stellar winds causing $F > 1$. The massive cloud complex associated with the Orion nebula (at *ca.* 470 pc) has been shown to be an extended source of γ-rays by Wolfendale (1980), from examination of SAS-2 data, and Caraveo *et al.* (1980), with COS-B. Both sets of workers agree that F is, if anything, slightly less than one. Now just one part of the Orion nebula contains 325 flare stars compared with only four for ρ-Oph (Gurzadyan 1980) so that winds from the flare stars in ρ-Oph are unlikely to cause $F > 1$. An even stronger argument comes from some preliminary data for the Gum nebula (distance *ca.* 400 pc). This object is an extended H II region containing two very active stars which appear to generate a wind energy about 400 that expected in ρ-Oph (with data from Reynolds 1976). Strong & Wolfendale (this symposium) present preliminary evidence from SAS-2 data for this

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object, too, having been seen in γ-rays with $F \approx 1$, so that it seems unreasonable to expect the flare stars in ρ-Oph to contribute much to the ambient cosmic-ray flux.

We conclude from these studies (and others, see Wolfendale 1980) that there is as yet no compelling evidence for $F > 1$ in any of the local molecular clouds.

3. A statistical analysis for the whole Galaxy

The technique adopted is to take a model for the distribution of giant molecular clouds in the Galaxy, irradiate them with an ambient cosmic-ray flux and to find by Monte-Carlo techniques how many apparently discrete sources would be detected. The angular resolution of the COS-B experiment is included. The procedure has been carried out with modest accuracy for the H_2 distribution of Gordon & Burton (1976) but, so far, only very approximately for the more recent variants of Blitz & Shu (1980) (see table 1)†. In all cases the mass of the giant molecular cloud (assumed unique in this analysis) was chosen to give, roughly, the correct mean latitude of the detected 'sources'. Comparison is made with the observed numbers of sources reported by Wills *et al.* (1980), the technique for source detection following that described by Hermsen (1980). Table 1 gives the results (these all relate to $E_\gamma > 100$ MeV).

Table 1

H_2-distribution	total mass/$M_\odot$	mass of a cloud/$M_\odot$	fraction predicted for $S > 10^{-6}$ cm^{-2} s^{-1}	fraction predicted for $S > 2\times10^{-6}$ cm^{-2} s^{-1}
Gordon & Burton (1976)	2×10^9	7×10^5	≈ 100 %	≈ 200 %
Blitz & Shu (*SS′*) (1980)	7×10^8	4×10^5	≈ 40 %	≈ 20 %
Blitz & Shu (*GB′*) (1980)	5×10^8	3×10^5	≈ 30 %	≈ 60 %

It is premature to draw a firm conclusion as to the fraction of the 'discrete' sources that are giant molecular clouds not only because insufficient trials have so far been made but there is doubt about the correct form of H_2 distribution to take. The work of Few (1979) on formaldehyde is probably the best to take; it is close to that of Gordon & Burton (1976) in form but down by a factor 2 in total mass (i.e. there is support for an H_2-distribution between rows 1 and 2 in the table) so that a value for the fraction of *ca.* 40 % would seem to be the best estimate at present.

References (Issa & Li Ti-pei)

Baart, E. E., de Jager, G. & Mountfort, P. I. 1980 (In the press.)
Blitz, L. & Shu, F. H. 1980 *Astrophys. J.* **238**, 148–157.
Caraveo, P. A. *et al.* 1980 *Astron. Astrophys.* **91**, L3–L5.
Cassé, M. & Paul, J. A. 1980 *Astrophys. J.* **237**, 236–243.
Few, R. W. 1979 *Mon. Not. R. astr. Soc.* **187**, 161–178.
Fichtel, C. E. *et al.* 1975 *Astrophys. J.* **198**, 163–182.
Gordon, M. A. & Burton, W. B. 1976 *Astrophys. J.* **208**, 346–353.
Gurzadyan, G. A. 1980 In *Flare stars* (ed. Y. Terzian), p. 200. Oxford: Pergamon Press.
Hermsen, W. 1980 Ph.D. thesis, University of Leiden.
Issa, M. R., Strong, A. W. & Wolfendale, A. W. 1980 *J. Phys.* G (To be published.)
Jenkins, E. 1976 In *The structure and content of the galaxy and galactic gamma rays*, GSFC X-662-76-154, p. 239 (Tech. Inf. Div., code 250, Goddard Space Flight Center, Maryland, U.S.A.).
Morfill, G. E., Volk, H. J., Forman, M., Bignami, G. F., Caraveo, P. A. & Drury, L. 1980 *Astrophys. J.* (Submitted.)

† See note added in proof.

Paul, J. A., Cassé, M. & Montmerle, T. 1980 In *The origin of cosmic rays*, 94th I.U.P.A.P./I.A.U. Symp., Bologna (ed. G. Setti, G. Spada & A. W. Wolfendale). Amsterdam: D. Reidel.
Reynolds, R. J. 1976 *Astrophys. J.* **206**, 679–684.
Wills, R. D. *et al.* 1980 In *Non-solar gamma rays* (Cospar Symp.) (ed. R. Cowsik & R. D. Wills), *Adv. Space Explor.* **7**, 43.
Wolfendale, A. W. 1980 In *The origin of cosmic rays*, 94th I.U.P.A.P./I.A.U. Symp., Bologna (ed. G. Setti, G. Spada & A. W. Wolfendale). Amsterdam: D. Reidel.

Note added in proof, 20 *March* 1981. More recent calculations show that the fractions predicted for SS' and BB' in table 1 are in the range 50–70%.

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