1.4 SEARCHES FOR γ-RAYS FROM THE CRAB NEBULA AND ITS PULSAR

J. V. JELLEY

Nuclear Physics Division, Atomic Energy Research Establishment, Harwell, Berkshire, U.K.

Abstract. The Crab Nebula has been regarded as the most promising celestial object to investigate for the detection of γ-rays. γ-ray emission might be expected from either the synchrotron or the inverse Compton mechanism. Periodic γ-ray emission could come from the pulsar, but no theory has yet been developed for such objects. Searches for γ-rays from both the Crab Nebula and the Crab pulsar made by a number of groups are described. Limits have been set to the γ-ray emission from both objects which are only a little above the extrapolated optical and X-ray fluxes.

1. Introduction and History

It is interesting to reflect that the idea of searching for γ-rays from celestial objects occurred as far back as the late fifties, some years prior to the discovery of X-rays, either from the Galaxy, or from point sources. Historically, of course, this arose because there were at that time no rockets or satellites to carry X-ray instruments above the atmosphere, and it was early appreciated that atmospheric absorption would preclude observations either from the ground or even from balloon altitudes. Over the years however, a very considerable effort has been expended in the development of γ-ray astronomy, using a wide variety of techniques, with equipment which has been flown on balloons, mounted in satellites, and also ground-based. In spite of these great efforts, γ-ray astronomy is only now just beginning to bear fruit, and interest has naturally been somewhat overshadowed by the impact of the impressive results obtained in the X-ray field.

While γ-rays are sufficiently penetrating to reach down to balloon altitudes, enabling at least relatively simple experiments to be conducted without recourse to rocket and satellite techniques, various factors emerge which combine to make γ-ray astronomy considerably more difficult than X-ray astronomy. First is the question of the low fluxes. Even on the basis of energy per unit bandwidth, most celestial sources of X-rays have spectra which fall away with increasing frequency, and since all X-ray and γ-ray detectors are essentially quantum counters, the effect is still more pronounced. Thus, to obtain even reasonable rates, short rocket flights are quite inadequate. It is essential to have large collecting areas and long integrating times. Rockets therefore cannot be used. The second problem is that of the cosmic-ray background of charged-particles; on average the γ-ray component of the cosmic-radiation is known to be $\leqslant 10^{-3}$ of the charged-particle component. It is therefore very important to have good discrimination against the charged-particle component.

γ-ray astronomy can be said to date from a paper by Morrison (1958) in which he outlined some of the processes which could be important for the production of γ-rays from the Galaxy and specific celestial objects. A large number of review

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articles on the subject are now available and we will mention just three. The first (Fazio, 1967) and the second (Ginsburg and Syrovatskii, 1965), cover the whole field, with emphasis on the physics of the production mechanisms and the astrophysical situations involved, while the third (Kraushaar, 1969) is primarily concerned with the instrumentation and detection aspects of the problems.

2. Techniques

The γ-ray spectrum extends approximately from $\sim$500 keV to $\sim 5.10^{13}$ eV, a vast range, about eight decades. It is therefore not surprising that a wide variety of techniques have been developed to encompass this great span of energy (Kraushaar, 1969). There are however two broad subdivisions, the band 10 MeV–1 GeV being covered by instruments carried on balloons and in satellites, and a higher band, 10^{11} eV–10^{13} eV which is accessible by ground-based observations, using the Cherenkov night-sky technique (Jelley and Porter, 1963). As we shall see later, the most important work on the Crab Nebula carried out so far, has been in the region 30 MeV–1 GeV (balloons) and in the band 9.10^{10} eV–5.10^{12} eV (ground-based Cherenkov instruments). The most promising instruments under development at the moment are the vidicon spark chambers (and combinations of spark chambers and nuclear emulsions) and the enclosed gas Cherenkov detectors (Helmken and Hoffman, 1970). Space prohibits a more detailed discussion of techniques, but I have however attempted to summarise the situation by the diagram shown in Figure 1.

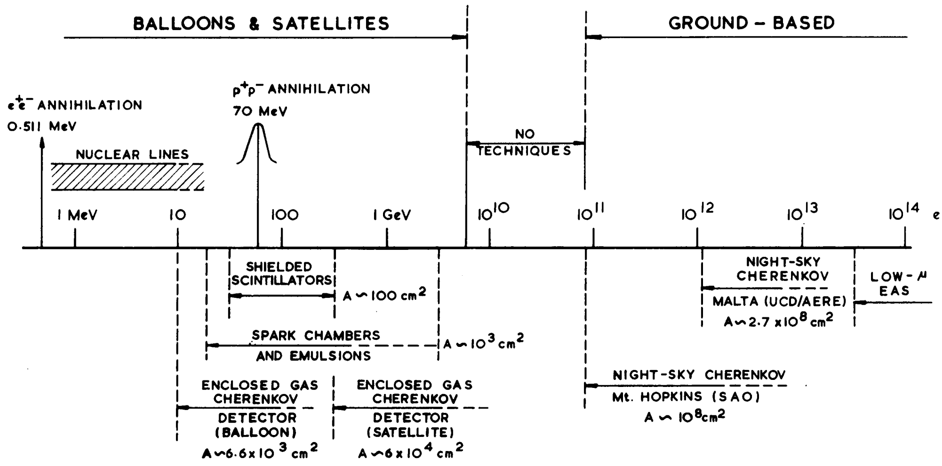


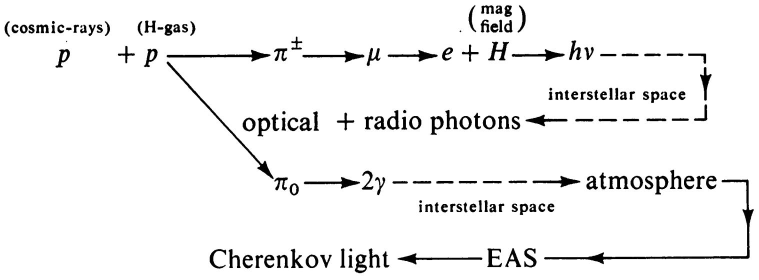
Fig. 1. The γ-ray spectrum and available techniques.

3. The Crab Nebula: Theoretical Models

It has long been realised (Ginsburg and Syrovatskii, 1964; Shklovskii, 1960) that the Crab Nebula is probably the most important celestial object in which high-energy cosmic-rays may be generated, and hence it has been accepted for a long time that it is likewise the most promising object from which to find γ-rays. All the optical and radio observations of the nebula alone, leaving out the additional considerations involved by the discovery of its pulsar, lead to these conclusions, and many sections of the work by Ginsburg and Syrovatskii (1964) are devoted to this theme. In most of these models both synchrotron radiation (Ginsburg and Syrovatskii, 1964) (magneto-bremsstrahlung) and the inverse Compton effect (Felten and Morrison, 1963) play important rôles, taken either separately or together. In most astrophysical situations and especially in the Crab, these two mechanisms are more important than nuclear processes and collisional bremsstrahlung, for their contribution to the generation of γ-rays.

Early predictions that the Crab might be expected to yield a measurable flux of high-energy γ-rays were due to Burbidge (1959) and to Cocconi (1960).

Assuming that all the continuum optical and radio emission from the nebula arises directly from synchrotron radiation from electrons, they suggested that if all these electrons were continually being generated by π–μ–e decays, then one could calculate a γ-ray flux from the decay of the accompanying π_0-mesons. It was proposed that both the $\pi^{\pm}$ and π_0-mesons were in turn generated by the collision of cosmic-ray protons with the nuclei of hydrogen gas known to be present in the nebula. The chain of reasoning on this model is illustrated as follows:



On this model a γ-ray flux of 1.6×10^{-7} photons cm^{-2} sec^{-1} at the Earth, for $E_\gamma \sim 10^{12}$ eV was predicted (Cocconi, 1960). Early observations (Chudakov *et al.*, 1962) however set an upper limit of 5×10^{-11} photons cm^{-2} sec, at 5×10^{12} eV, a factor at least 3000 below that predicted on Cocconi's model. Chudakov *et al.* (1962) were therefore able to show that the high-energy electrons in the nebula were not secondary products from π-meson decay, and since the lifetime of these electrons is so short compared to the age of the Crab, it was therefore deduced that the electrons must continuously derive their energy from some unknown source and undergo subsequent acceleration.

The Compton-synchrotron model of the Crab, by Gould (1965), was the next significant step, and served for some years as a basic model on which to hang the experimental results to be discussed later. Gould was able to show that the optical and radio photons generated by synchrotron radiation would be Compton-scattered in turn by the same electrons which themselves generated the synchrotron radiation, thus creating a photon spectrum extending right up into the γ-ray region. To simplify the calculations, Gould took a single value of $H = 10^{-4}$ G and two basic photon

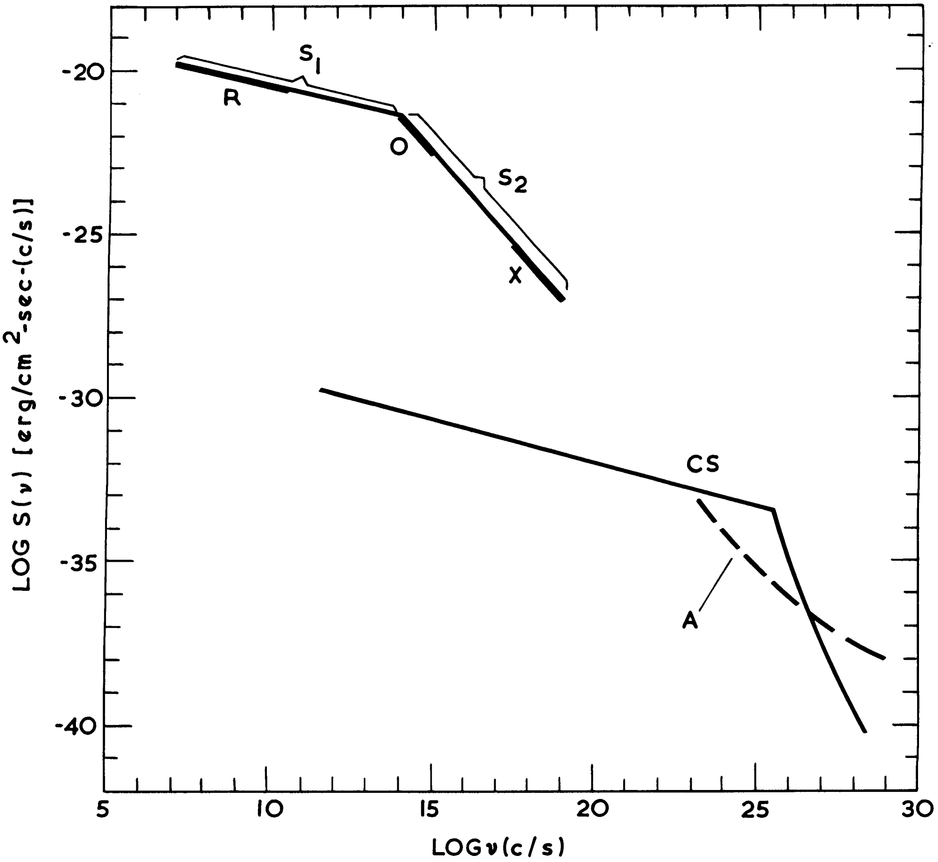


Fig. 2. The Compton-synchrotron spectrum *CS* calculated by Gould (1965) from the observed spectra S_1 and S_2, derived from measurements in the radio, optical and X-ray regions, *R*, *O*, and *X* respectively. The extension *A*, due to Apparao (1967) is a Compton spectrum deduced from interactions with the Universal Microwave Field.

spectra, Figure 2, S_1 corresponding to the radio-optical region, and S_2 the optical-X-ray region. The slopes of these power-law spectra are 0.27 and 1.1 respectively. We thus have two electron spectra interacting with two photon spectra. Assuming S_1 and S_2 are generated within spheres of angular diameter 4′ and 2′ respectively, Gould derived the high-energy photon spectrum *CS* shown in Figure 2.

A more refined calculation, with improved input data derived from a greater knowledge of the synchrotron spectra, has since been carried out by Rieke and Weekes (1969). In this development of the Gould model the authors calculated the γ-ray spectrum for two values of the magnetic field, 10^{-4} and 3×10^{-4} G respectively, and considered two specific models, one assuming the X-rays in the Crab followed a synchrotron spectrum, and the other, that the X-rays cut off sharply at 10^{16} Hz. They also considered the Compton scattered photons from the 3 K background radiation, assumed to permeate the nebula throughout. The theoretical spectra

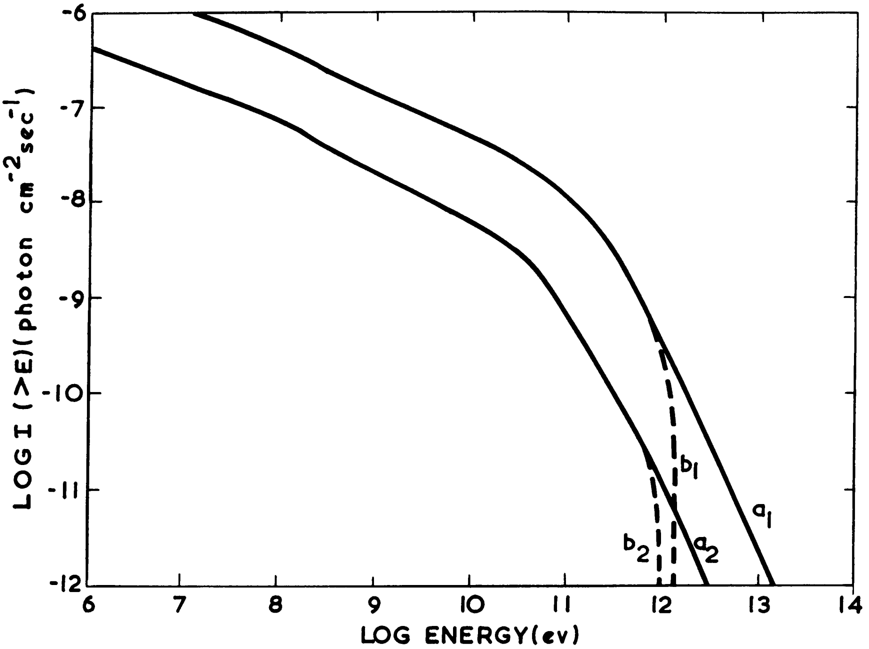


Fig. 3. Theoretical Compton-synchrotron spectra calculated by Rieke and Weekes (1969). Curves a_1 and b_1, $H = 10^{-4}$ G, a_2 and b_2; $H = 3 \times 10^{-4}$ G. The a-curves assume that the X-ray flux is synchrotron radiation. The *b*-curves are derived assuming the synchrotron spectrum cuts off at 10^{16} Hz.

derived by these authors is shown in Figure 3. We note that it differs in two respects from the earlier Gould model, Figure 2. The absolute fluxes are lower and the spectra are steeper, at the higher energies. While the Rieke-Weekes model represents the best available at the present time, it does not allow either (a) for a general variation of the magnetic field across the nebula, or (b), for spatial fluctuations of this field. A much greater knowledge of the distribution of the field within the nebula is clearly required before substantial improvements can be made.

In connection with the 3K background radiation it should be mentioned that this was also considered by Apparao (1967). He showed that this would cause a substantial extension to the Gould spectrum, at the very highest energies, as shown in Figure 2.

4. The Crab Pulsar; Theoretical Models

All that has been said so far was based on our knowledge of the Crab nebula prior to the discovery of its pulsar, and its subsequent identification with the S_p-component of the central double star. However, the discovery of NP 0532 and the vast amount of data on its characteristics and spectrum, from radio frequencies right through to hard X-rays, has naturally caused one to ask what modifications may be necessary to the theories of the nebula as a whole. There are many facets to the problem and some of these are directly concerned with γ-rays, and at once raise the question of whether we might expect pulsed γ-rays from the Crab, either instead of or as well as steady γ-rays from the extended regions of the object.

The first point and a very satisfying conclusion, is that it has been found that the energy-loss of the pulsar, represented by its rate of slowing-down, $\sim 10^{38}$ ergs $\sec^{-1}$, very closely matches the rate of energy-loss by radiation, from the nebula as a whole. This suggests first, that the pulsar is coupled tightly to the nebula, and secondly, that the pulsar is indeed the basic energy-source of the Crab, at least at the present epoch.

There are basically two models of the pulsars, both assuming that they are rapidly rotating neutron stars. In the first (Gold, 1968; 1969) it is assumed the radiation occurs out at a radius corresponding to the velocity-of-light circle, and in the second, that the radiations arise on the surface of the pulsar, and emerge from the magnetic poles, on the various forms of the oblique rotator model (Pacini, 1967; Gunn and Ostriker, 1969; Bertotti *et al.*, 1969).

On an energy basis it has become clear that NP 0532, and likewise other pulsars, may be adequate to accelerate all cosmic-rays, with perhaps the exception of those of the very highest energy. In particular Ostriker (1969) shows that the intensity of the 30 Hz low-frequency magnetic field is sufficient to produce direct acceleration of cosmic-rays by the electric fields induced by the varying magnetic fields, up to energies as high as 10^{18} eV. It has been suggested elsewhere at this Meeting (Rees, 1971) that the entire field throughout the Crab nebula may be modulated at 30 Hz and indeed that it may even be wholly an AC field. This suggestion immediately raises doubts as to whether the Gould (1965) or Rieke-Weekes models of the γ-ray emission are valid, for the synchrotron orbits will be so modified if the H-field is AC, that the calculations become extremely difficult. For example Fazio (private discussion) has suggested that we should perhaps take a dipole magnetic field which falls off as $(1/r^3)$ right from the surface of the star, where H is believed to be $\sim 10^{12}$ G, though again there are problems, for there is clearly some discontinuity at the velocity-of-light circle. Suffice it to say that at the time of this Meeting, no-one has so far presented a quantitative theory of the production of γ-rays from the Crab and its pulsar, which include these new considerations. In the absence of such models it is natural that the γ-ray astronomers have been searching for *periodic* γ-rays from the Crab, at all the energy bands accessible with the various techniques available.

In spite of my general remarks on these problems, some attempts have in fact already been made (Apparao, 1969), to calculate the γ-rays expected from the Crab, assuming now that its pulsar may be the essential and basic source.

A reliable theory cannot however be expected until it is established whether the periodic radio, optical and X-ray emissions arise from the velocity-of-light circle or from the magnetic poles of an oblique rotator; there are many other problems as well.

5. Searches for Steady γ-Rays from the Nebula

A very extensive list of groups have for many years been searching for a steady source of γ-rays from the Crab Nebula, and so far none have been found, at least not at a confidence level sufficiently high to be acceptable to all concerned. The principal investigators have been from MIT, AS and E, Rochester, Cornell, Rice, NASA, Bristol, Southampton, SAO, UCD and AERE. This is by no means a complete list. While no positive results have been obtained, there are numerous upper limits and these are listed in Table I. Even these upper limits however have already provided significant constraints to the theoretical models. We have previously mentioned that

TABLE I

Measured upper limits to the steady γ-ray flux from the Crab Nebula

Threshold γ-ray energy	Upper-limit steady flux photons cm^{-2} sec^{-1}	Experiment	References
30 MeV	1.5×10^{-4}	Frye and Smith (1966)	Duthie (1968)
50 MeV	6.6×10^{-4}	Kraushaar *et al.* (1965)	Duthie (1968)
100 MeV	5×10^{-5}	Cobb *et al.* (1965)	Duthie (1968)
1 GeV	2×10^{-5}	Rochester spark chamber	Duthie (1968)
5.10^{12} eV	5×10^{-11}	Chudakov *et al.* (1962)	Duthie (1968)
5.10^{12} eV	1×10^{-10}	Fruin *et al.* (1964)	Duthie (1968)
10 MeV	4.2×10^{-3}	Fichtel and Kniffen (1965)	Fichtel *et al.* (1969)
3×10^{11} eV	2.3×10^{-6}	Sekido *et al.* (1963)	Fazio (1967)
10^{15} eV	10^{-14}	Toyoda *et al.* (1965)	Fazio (1967)
2×10^{12} eV	1.5×10^{-10}	Long *et al.* (1966) Fegan *et al.* (1967)	Long *et al.* (1966) Fegan *et al.* (1968)
4×10^{12} eV	8×10^{-11}	Fazio *et al.* (1968)	Fazio *et al.* (1968)
3×10^{12} eV	7×10^{-11}	Fazio *et al.* (1968)	Fazio *et al.* (1968)
2×10^{12} eV	1×10^{-10}	Fazio *et al.* (1968)	Fazio *et al.* (1968)
1.7×10^{11} eV	2.0×10^{-10}	Fazio *et al.* (1969)	Fazio *et al.* (1969 c)
1 GeV	1.2×10^{-5}	Delvaille *et al.* (1967)	Delvaille *et al.* (1968)
50 MeV	1.7×10^{-5}	Frye and Wang	Frye and Wang (1969)
150 MeV	9.0×10^{-6}	Frye and Wang	Frye and Wang (1969)
500 MeV	5.0×10^{-6}	Frye and Wang	Frye and Wang (1969)
30–100 MeV	2.7×10^{-4}	Fichtel *et al.* (1969)	Fichtel *et al.* (1969)
>100 MeV	1.8×10^{-4}	Fichtel *et al.* (1969)	Fichtel *et al.* (1969)

Chudakov's limits directly implied that the fast electrons in the Crab cannot be secondary to cosmic-ray proton collisions with hydrogen gas. Another example is that limits can be set on the magnetic field, Fazio *et al.* (1969b) having shown that the average field H must be $\geqslant 1.2 \times 10^{-4}$ G; this in turn sets a constraint on the expected flux at 100 MeV, on the Compton-synchrotron model, at a level of $\phi_\gamma \sim 10^{-7}$ photons cm^{-2} sec^{-1}, a figure, we notice that is still nearly two orders of magnitude lower than the recent limits set by Frye and Wang (1969).

6. Searches for Periodic γ-Rays from NP 0532

It is of course only during the last two years that it has been feasible to consider experiments of this kind. The very low counting rates and γ-ray fluxes expected, require long integrating times, and this, combined with the high repetition frequency of

NP 0532, implies extremely high precision in the timing accuracy, and frequency-dividing circuits used in the periodicity analyses. In work of this type, particularly on this the fastest pulsar, it has been found to be exceedingly difficult to preserve phase in the analysing procedures over periods of more than a few hours. While ground-based observations can on occasion enjoy the luxury of on-line calibration from light-pulses (Fazio *et al.*, 1971) from the star, balloon-borne experiments necessitate continual corrections for the position and velocity of the balloon, at least for observations of several hours.

It is for just these reasons that the vast mass of earlier γ-ray data on the Crab taken prior to the discovery of the pulsar, cannot subsequently be analysed for periodicity, as the data were not in general recorded in real time, with the precision required, namely ~1 part in 10^8 over a few hours.

Several attempts have however now been made to detect γ-rays from the Crab and these, mostly upper limits, are listed in Table II.

TABLE II

Measured upper limits to the pulsed γ-ray flux from the Crab Nebula

Threshold γ-ray energy	(NP 0532) Pulsed γ-ray flux photons cm^{-2} sec^{-1}	Experiment
1.3×10^{13} eV	$\leqslant 3 \times 10^{-12}$	Charman *et al.* (1969)
$(1 \rightarrow 3) \times 10^{12}$ eV	$\leqslant 2.9 \times 10^{-11}$	Charman *et al.* (1969)
$(2 \rightarrow 4) \times 10^{12}$ eV	$\leqslant 2.7 \times 10^{-11}$	Charman *et al.* (1969)
$(2 \rightarrow 4) \times 10^{12}$ eV	$\leqslant 3.2 \times 10^{-11}$	Charman *et al.* (1969)
1.2×10^{11} eV	$\leqslant 2.6 \times 10^{-10}$	Fazio *et al.* (1969 a)
1.1×10^{12} eV	$\leqslant 3.0 \times 10^{-11}$	Fazio *et al.* (1969 a)
50 MeV	$\sim 10^{-5}$	Vasseur *et al.* (1970)

The reader will notice, once again, that nearly all the observations have only led to upper limits. Of the observations listed, one only, that made by a French-Italian group (Vasseur *et al.*, 1970) claimed a positive effect which appeared, at least superficially, to be significant. This claim was however subsequently discounted, by at least two groups (Charman and White, 1970; Delvaille and McBreen, 1970), on statistical grounds.

Subsequent however to this Symposium, but prior to the publication of its Proceedings, the author has heard that the Bristol group now have evidence, at a very reasonable level of significance, for periodic γ-rays from NP 0532 in the energy region 0.6 MeV–12 MeV; in this work they used a periodicity calculated by UCD, Dublin. If this observation can be confirmed, it represents the first detection of γ-rays from NP 0532.

7. Discussion

Considering the large efforts expended to find γ-rays from the Crab and/or its pulsar, the results have been disappointing indeed, especially as this object has always been cited as the most profitable one at which to peer, since it was expected to be the most likely source of cosmic-rays.

One naturally asks 'why no γ-rays'?, or, if they are produced, 'what becomes of them'? Photon-photon absorption has been considered but it seems rather unlikely. In the relatively short distances of $\sim$1.3 kpc, this absorption mechanism is believed to be negligible (Gould and Schréder, 1966; Jelley, 1966a) unless there are intense background radiations in the U.V. and shorter wavelengths, which have not yet been detected. It has however been suggested (McBreen, 1971) that if any γ-rays are generated very close to the surface of the pulsar, these may be absorbed within the source region itself (Jelley, 1966b). The problem here is that the γ-rays and the photons with which they collide will be travelling with respect to one another on almost parallel paths, thereby raising the threshold of the absorption process and lowering the effective cross-section, a point mentioned recently by Ginsburg (1970).

On the experimental side the efforts will clearly continue. Large-area spark-chamber detectors and large gas Cherenkov detectors will be flown on balloons and satellites, and it is therefore still hoped that high energy γ-rays from the Crab and/or its pulsar will eventually be found.

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Discussion

J. P. Ostriker: A model-independent question of fact: are the γ-ray upper limits above or below the extrapolated X-ray spectrum? Or is the extrapolation made over too great a range to be secure given the uncertainty of the X-ray spectral index?

J. V. Jelley: I think the γ-ray upper limits fall *below* the extrapolated X-ray line. I do not think this is meaningful however, as it is such a distant extrapolation.

J. E. Baldwin: The values I quoted lie above the extrapolated X-ray spectrum. They may not be the lowest limits presently available. There is also the problem of converting a total flux above some energy limit into a flux at a given energy. This may account for the discrepancy with Jelley's plot.

G. Fazio: Whether the 100 MeV upper limits lie above or below the extrapolated flux depends on the spectral index used (i.e. $\alpha = -2.0$ or -2.2). The extrapolation has to be done over 3 orders of magnitude at least. In either case the upper limits are within about one order of magnitude of the flux predicted by extrapolation.

G. Share: Our group in the Laboratory of Cosmic Ray Physics at NRL has flown a telescope sensitive to gamma rays with energies above 10 MeV. The telescope consists of a combination of emulsion, spark-chamber and counters, and is capable of attaining an angular resolution of 2° above 20 MeV. Successful balloon flights were performed on 25 September and 25 October 1969. In both flights the Crab Nebula was the object of our search. We had hoped to present results of the 25 October flight at this meeting but the analysis was not completed in time. Results from a search for pulsed radiation from the Crab will be available in the near future.