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THE CRAB NEBULA AT HIGH ENERGIES – A HISTORICAL PERSPECTIVE

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RESUMEN

La Nebulosa del Cangrejo, remanente de una supernova cercana en 1054, exhibe muchos fenómenos de interés para los astrofísicos de alta energía. El continuo óptico sin rasgos distintivos en la región central emite rayos X y energía de rayos gama con un espectro que posiblemente se extiende hasta 10^{12} eV. Se cree que esta emisión se debe a la radiación sincrotónica de electrones relativistas en un campo de la nebulosa 6 x 10^{-4} gauss, los cuales están siendo acelerados todavía. La nebulosa está aparentemente impulsada por la desaceleración de la estrella de neutrón girando a 33 ms cercana al centro de la nebulosa. Este pulsar emite radiación sobre el intervalo completo en radio, óptico, rayos X y rayos gama. A pesar de que la mayoría de los descubrimientos básicos fueron hechos en los 60's y 70's, los datos recientes obtenidos de observatorios como el *Telescopio Espacial Hubble* y el *Compton Gamma Ray Observatory*, están proporcionando nuevos y significativos detalles de los procesos en el Cangrejo.

ABSTRACT

The Crab Nebula, the remnant of a nearby supernova in 1054, exhibits many phenomena of interest to high energy astrophysicists. The featureless optical continuum in the central region emits X-rays and gamma-ray energy with a spectrum possibly extending to 10^{12} eV. This emission is believed due to the synchrotron radiation of relativistic electrons in a 6×10^{-4} gauss nebular field, which are still being accelerated. The nebula is apparently powered by the spin-down of the 33 ms rotating neutron star near the center of the nebula. This pulsar emits radiation over the entire radio, optical, X-ray and gamma-ray range. Although most of the basic discoveries were made in the 1960's and 1970's, recent data from ground based observatories, the *Hubble Telescope,* and the *Compton Gamma Ray Observatory* are providing significant new details of processes in the Crab.

Key words: **ISM: SUPERNOVA REMNANTS — PULSARS: INDIVIDUAL (CRAB NEBULA)**

1. INTRODUCTION

The Crab Nebula is probably the single most well-studied celestial object beyond the solar system. Since the dawn of radio astronomy and the space age, the Crab has been almost uniquely regarded as an object exhibiting high energy phenomena. Many discoveries in the early days of x-ray and gamma-ray astronomy were made first from the Crab. Early results showed spectra extending beyond the typical 1–10 keV range of X-ray astronomy into the hard X-ray and gamma-ray range. In particular, the discovery of the 33 ms pulsar in the nebula added a new dimension to observational studies, and to interpretational possibilities for high energy astrophysics.

In this paper, the historical context of the work on the Crab is indicated, and the early discoveries of high energy phenomena are described. Recent work on the size and shape of the synchrotron emitting region is shown. The pulsed profile of PSR 0531+21 (the 33 ms Crab pulsar) are discussed and the latest broad band high energy spectrum of both the nebular component and the pulsar are presented. The Crab is still an exciting object for study, with the revival of interest by optical and UV astronomers, as well as high energy astrophysicists on this fascinating object.

2. OPTICAL PROPERTIES

As is well known, the Crab Nebula is an expanding remnant of a supernova explosion observed by Chinese Court astronomers in the year 1054. The object was studied later by Western astronomers, and in fact is the first object, M1, in the Messier catalog of about one hundred extended celestial objects. In the 1940's and 1950's Baade (1942) and Minkowski (1942) did extensive optical work in conjunction with studies of other, more distant supernova. From the Chinese records, the light was inferred to decay in about 60 days, typical of Type 1 supernova. Figure 1 shows a black and white version of an often reproduced photo of the Crab taken through the Palomar 5-m telescope. The object is a few arc minutes in size; the emission in the outer filamentary regions are primarily due to excited states of O and N; the central region is dominated by a featureless blue continuum. Although almost all of the stars in the photo are background stars un-associated with the Crab, one object, the "south preceding star" was suggested by Baade (1942) to be the left-over star from the explosion. Later this was verified remarkably with its identification with the 33 ms radio/optical/X-ray pulsar NP0532 in the Nebula (Lynds, Maran, & Trumbo 1969).

Various changes in the nebular structure with time were noted since the turn of the century; particularly "wisps" and structures in the central region were noted to form and disappear (Scargle 1969). Shklovsky, who took particular interest in the object, noted it was as if the Nebula "breathes" (Shklovsky 1960). Apart from the work of Scargle on structural variations in the central region, Trimble (1968) on emission phenomena in the filaments, and the photometeric work of O'Dell (1962) few optical studies were performed in the 60's and 70's. Particularly after the discovery of X-ray emission (Bowyer et al. 1964a) and the pulsar (Staelin & Reiferstein 1968), the Crab was regarded as an object primary of interest to high energy astrophysicists.

Davidson & Fessen (1985) have recently written a review of the optical work current as of about 1985, which set the stage for more recent studies. Table 1, taken from their paper, summarizes properties of the nebula. They adapt the distance to be 1830 kpc. The object is in fact an oblate spheroid, expanding at a rate of about 1100 km s^{-1}. The present size and expansion rate imply the filaments are being slowly accelerated. Other relevant data are also given in Table 1. The radio, optical, and X-ray emissions from the Nebula are of the same order.

TABLE 1
CRAB NEBULA PROPERTIES

Distance:	$\sim$ 1500–2000 pc. (D&F adapt 1830 pc)
Size:	$1.9' \times 3.4' \rightarrow 1.1 \times 1.8$ pc oblate spheroid
Extinction:	$A_v = 1.46 \pm 0.12$
Filaments:	[0III], [0II], [NII] etc. 10^{16}-10^{17} cm thick
Expansion:	$\sim$ 1100 km $s^{-1} \rightarrow$ Acceleration
Luminosity:	$(L_{rad} \sim 3.7; L_{opt} \sim 0.6; L_x \sim 1.2) \times 10^{37}$ ergs/sec $L_{tot} \sim 1.4 \times 10^{38}$ (d/1830 pc)^2 ergs/sec
Mass:	1-5 $M_\odot$ (excluding pulsar) (D&F adopt 2–3 $M_\odot$)
Composition:	He/H $\sim$0.6 +0,N.

3. SYNCHROTRON NEBULA

Shklovsky (1960) argued that the blue continuum emission in the central region could not be of thermal origin, as had been postulated by Baade and Minkowski. He suggested instead that the radio and optical continuum were due to synchrotron radiation by relativistic electrons in an $\sim 10^{-4}$ gauss magnetic field. This idea was supported considerably with the discovery that both the radio and optical emissions were polarized, and in certain regions this polarization approached 90% (Oort & Walraven 1956; Baade 1956). The overall polarization is 9%. Woltjer (1958) also examined some of the consequences of relativistic electrons in the nebula.

X-ray emission in the 1–10 keV range from the region of the Crab Nebula was initially discovered by workers at the Naval Research Laboratory (Bowyer et al. 1964a) and verified by a group at the Lawrence Livermore Lab (Grader et al. 1966). In a remarkable rocket experiment during a lunar occultation on 7 July 1964, Friedman and his colleagues at NRL managed to launch a rocket precisely timed to be at altitude during the few minutes the edge of the moon occulted the Nebula (Bowyer et al. 1964b). Figure 2 shows the results of this observation, which established several important facts. First, the Crab Nebula was indeed the emitting object from this region of the sky; second, the majority of the emission was extended, and therefore, not from a point source.

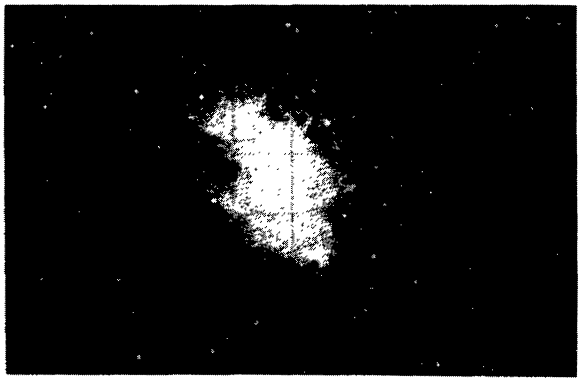

Fig. 1. Black and white version of a color photo of the Crab Nebula. The size is several arc minutes. The red emission from the filaments in the outer regions is due primarily to the excited states of N and O, while the blue continuum in the center is due to synchroton radiation in an $\sim 10^{-4}$ gauss field. The blue south star to the left of the central region is the pulsar.

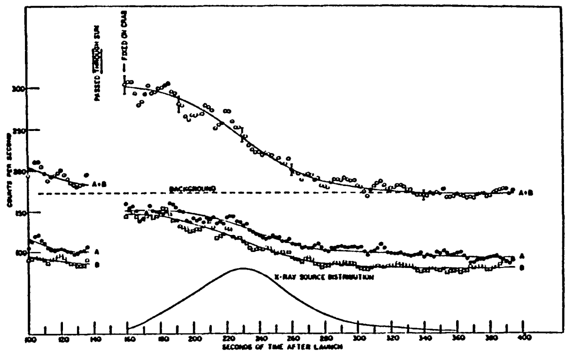

Fig. 2. The decrease in the counting rate from a NRL rocket observation during a lunar occultation on 7 July 1964 confirmed the X-ray source in this region of the sky was indeed the Crab Nebula, and that the bulk of the emission was associated with the extended nebula.

The possibility of emission from a neutron star, which would show a point source, had been postulated by Chiu & Salpeter (1964), Morton (1964), and possibly others. Oda and his colleagues later observed the X-ray emission in the 3–10 keV range with a modulation collimator, also on a rocket flight, and scanned the source in two directions, which better established the size and shape of the X-ray emitting region (Oda et al. 1967).

The extended emission also implies that X-rays are also of synchrotron origin. Woltjer (1964) examined the consequences of this, and generated the overall emission spectrum shown in Figure 3. If, indeed, the X-rays are due to synchrotron emission, the lifetime of the electrons is less than the light-size of the nebula, which implies a continuous acceleration of relativistic electrons in the nebula (Shklovsky 1966). Table 2 summarizes some of the properties of synchrotron electrons in the nebula, using the modern value of $\sim 6 \times 10^{-4}$ gauss for the average nebular magnetic field.

TABLE 2
CRAB NEBULA SYNCHROTRON RADIATION
$B = 6 \times 10^{-4}$ GAUSS

Range	Freq. (Hz)	E_B (GeV)	$T_{1/2}$ (yrs)
Opt	10^{15}	300	75
X-ray	10^{18}	10 000	2.5

X-ray and gamma-ray emission from cosmic sources at energies greater than about 20 keV, if sufficiently copious, can be observed from high flying balloons. During the early 1960's a number of ballooning groups around the world were beginning preliminary investigations into the possibility of high energy astronomy at very short wavelengths. This work received considerable impetus due to the discovery of hard X-ray emission during solar flares (Peterson & Winckler 1959), the early discoveries in soft X-ray astronomy (Giaconni et al. 1962), and the theoretical possibilities summarized in the seminal paper by Morrison (1958). Clark, following the work of his colleagues at MIT and ASE, was the first to observe a non-solar source, the Crab Nebula, from a balloon (Clark 1965). Work under Haymes at Rice (Haymes & Craddock 1966) and myself at UCSD (Peterson, Jacobson, & Pelling 1966) followed and determined the hard X-ray spectrum of the Crab over the 20–200 keV range. Figure 4 shows the results of the Rice and UCSD work circa 1968 (Haymes et al. 1968, 1969). The slope of power law continuum emission in the hard X-ray region agrees well with the modern accepted value for α

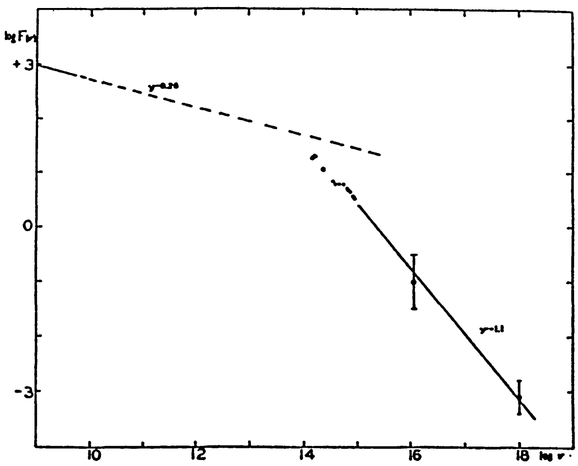

Fig. 3. The total spectrum of the Nebula continuum compiled by Woltjer provided a theoretical interpretation that all the emission, radio, optical, and X-ray, was due to a power law population of relativistic electrons.

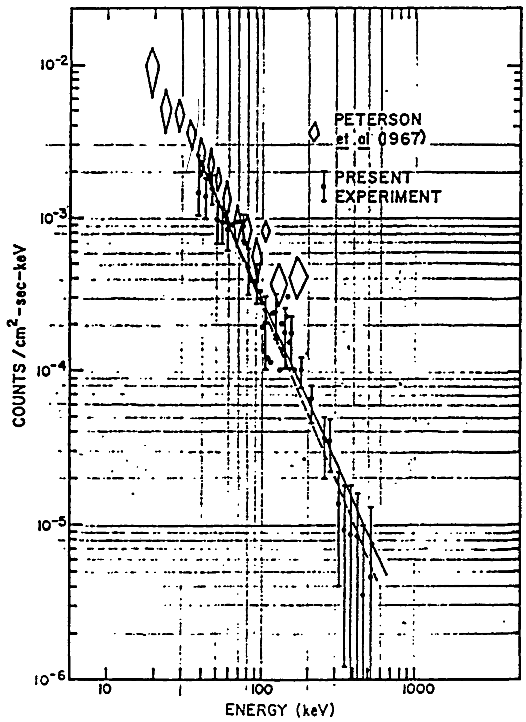

Fig. 4. The total spectrum of the Crab over the 20–500 keV range determined by Rice and UCSD confirmed the power law nature of the emission spectrum, and its extension to very high energies.

in dN/dE$\sim$ E$^{-(1+\alpha)}$ of α = 1.15. Haymes group actually had measured the spectrum to the highest energy $\sim$560 keV, during this period. All of the X-ray data through the discovery of the Crab pulsar in 1969 has been summarized in the proceedings of a symposium on the Crab Nebula (Peterson & Jacobson 1970). Later the Columbia group searched for polarization in soft X-rays with OSO–7 and determined a value of 16.1±1.4% for the overall polarization (Weisskopf et al. 1978).

4. THE PULSAR NP0532

Following the discovery of pulsed radio signals from cosmic sources and the suggestion that these may indeed be due to rotating neutron stars, the region of the Crab Nebula was searched for pulsations by radio astronomers. The radio pulsar in the Crab Nebula at 33+ms was discovered by Staelin & Reifenstein (1968) and extensively studied by Comella et al. (1969) and others. Optical pulsations were soon observed from the central region of the Nebula (Cocke, Disney, & Taylor 1969) and immediately confirmed by Nather, Warner, & Macfarlane (1969). These pulses were definitely associated with the "south preceeding star" of Baade by Lynds, Maran, & Trumbo (1969).

The optical pulsations, which were "extraordinarily blue" (Cocke et al. 1969), spurned X-ray astronomers to make new observations and search old data for evidence of pulsations. These were discovered originally in a March 1969 NRL rocket flight at a level of about 5% of the total emission (Fritz et al. 1969), and confirmed by groups at GSFC and Columbia. Bradt et al. (1969) at MIT verified the X-ray and optical pulses were in the same phase.

Pulsed hard X-rays were discovered by Haymes group at Rice (Fishman et al. 1969a,b) by re-analyzing data from their 4 June 1967 balloon flight. Fortunately the original data contained accurate timing signals, so the pulsed X-rays and their phase could be separated from the instrumental background and Crab Nebula

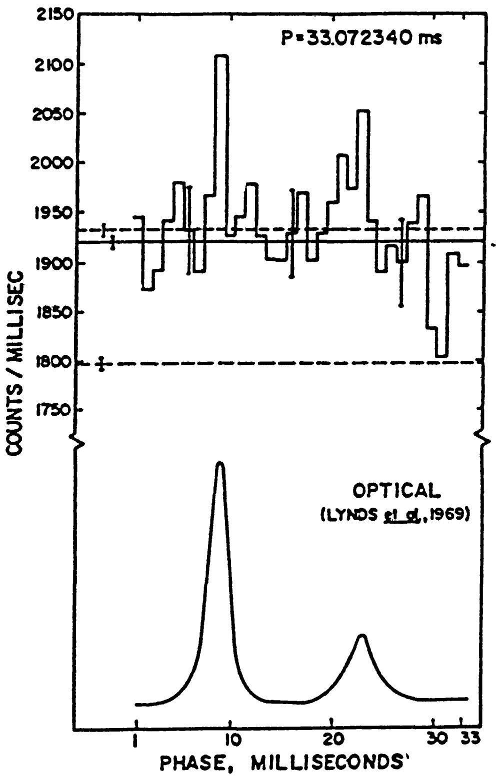

Fig. 5. The discovery from Rice balloon data of pulsed X-rays > 20 keV from NPO532 which were at the same period and phase as the extrapolated radio period for the observational epoch.

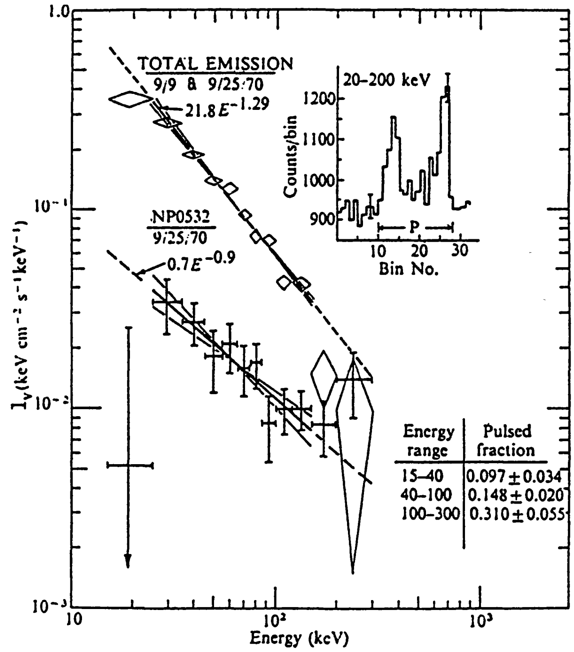

Fig. 6. A later measurement by UCSD separated the hard X-ray spectrum of the pulsed component from the nebula component, and showed the pulsed component has a flatter power-law spectrum in this energy range.

continuum. The "discovery" results are shown in Figure 5. Later workers followed and confirmed the results, and obtained the hard X-ray spectrum of NP0532. Figure 6 shows results obtained by UCSD from balloon flights on 9 and 25 Sept. 1970 (Laros, Matteson, & Pelling 1973) and compares the pulsed spectrum with that of the nebula over the 15–300 keV range. Pulsed X-rays constitute about 7–10% of the total Crab emission in this range, and the spectrum of the pulsar is clearly harder than that of the Nebula.

5. RECENT RESULTS

5.1. X-ray Continuum

During the 1970's, results from the High Energy Astronomical Observatories (HEAO's) and more sensitive balloon flights considerably improved upon the discovery results. The UCSD/MIT hard X-ray experiment on HEAO-1 accomplished phase resolved spectroscopy over the 18–200 keV range (Knight 1982). The HEAO-2 (Einstein Observatory) obtained a definitive pulse shape profile for the 0.1–4.5 keV X-rays, and the High Resolution Imager obtained the isoflux contours of soft X-ray emission shown in Figure 7 (Harnden & Seward 1984). A balloon measurement by a collaboration between Oda's group in Japan and UCSD using a modulation collimator/scintillation counter combination obtained the 22–64 keV X-ray isoflux contours shown in Figure 8 (Pelling et al. 1987).

Clearly the size of the Crab Nebula decreases slowly with size, but not at a rate consistent with simple direct propagation of a spectrum of relativistic electrons injected into the nebula by the pulsar. For similar reasons, simple diffusion or bulk motion of relativistic electrons, unaccompanied by acceleration, are unlikely.

Fig. 7. Isoflux contours of 2.4–3.6 keV X-rays determined from the Einstein Observatory superimposed on a photo which emphasized the blue continuum in the central region.

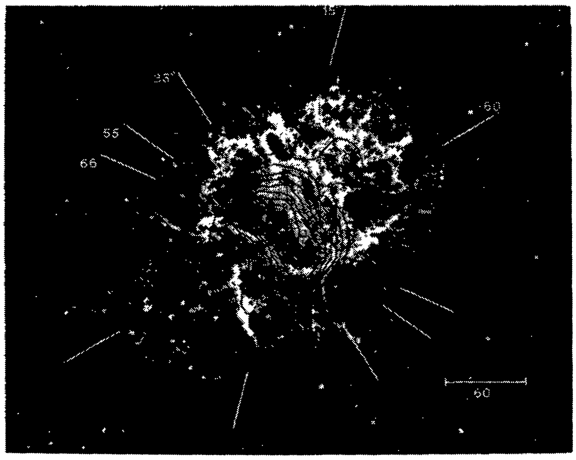

Fig. 8. Similar contours obtained from a UCSD balloon flight showed the region emitting 24–64 keV X-rays to be smaller than the optical continuum or X-ray regions.

Kennel & Coroniti (1984a,b) have proposed a "relativistic wind" model, in which the pulsar electrons essentially propagate directly in the inner regions of the Nebula, and form a shock at a distance of about 0.1 pc from the pulsar. Electrons in the outer regions of the nebula are continuously accelerated by this propagating shock, until the boundary region, which is characterized by the observable Hα envelope (Murdin & Clark 1981). The inner 0.1 pc hole may have been observed; structures in the inner region around the pulsar and their time variations are being intensively studied by workers using the *Hubble Space Telescope*. Doubtless details of the theoretical model will be improved as more understanding of relativistic shocks and acceleration process occurs, and as more observational results, particularly on the inner hole and on the dynamics of the filaments, are obtained.

5.2. Pulsed Gamma-Rays

Although many searches had been conducted for gamma-rays $\geq$ 0.5 MeV, no results either pulsed or unpulsed, from the Crab region had been reported as of the late 1960's (Peterson & Jacobson 1970). Pulsed gamma-rays were first reported at ~100 MeV by Browning, Ramsden, & Wright (1971) and by Albats et al. (1972). These were confirmed by the spark chamber on SAS-II (Thompson et al. 1977), and latter by a similar instrument on the Cos-B (Bennett et al. 1977). Pulsed gamma-rays in the 5–25 keV range were first reported by Kinzer et al. (1973). Pulsed gamma-rays from the Crab have not been reliably reported at TeV energies (Vacanti et al. 1991) so there must be a cut-off above 10 GeV. Figure 9 shows the pulsed spectrum of gamma-rays over the 50 keV – 10 GeV range for the leading pulse of the Crab pulsar (now called PSR 0531+21), based on recent data from the *CGRO* (Ulmer et al. 1995). Apparently the light curve of the Crab pulsar varies little in shape over the entire radio to gamma-ray range.

Gamma-ray emission from the magnetosphere of a rapidly rotating neutron star whose surface field is on the order of 10^{12} gauss has been explained in terms of two models: the "Polar Cap" model (Daugherty & Harding 1982) or the "Outer Gap" model (Cheng, Ho, & Ruderman (1986a,b). In either model, the gamma-rays are produced by positron-electron cascades in the intense field near the neutron star and by subsequent Compton up-scattering; the difference in models is primarily the location and electrodynamic conditions under which the cascade occurs. None of the models presently explain all the features of pulsed high energy phenomena; both models are undergoing considerable refinement (Harding & Daugherty 1993). The darkend line in Figure 9 shows the best fit to a recent outer gap model (Ho 1993). Transient gamma-ray events, likely associated with the pulsar or its immediate environment, reported by the *SIGMA* satellite (Gilfanov et al. 1994) have not been confirmed by the *CGRO* (Smith et al. 1966).

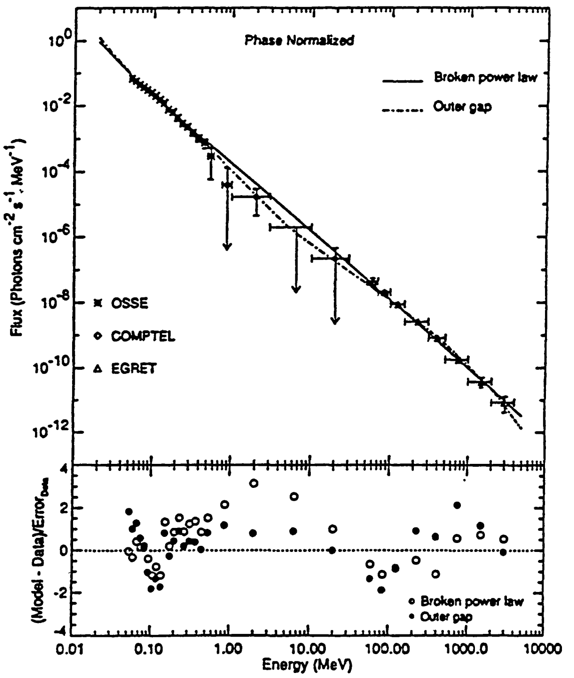

Fig. 9. The spectrum of PSR 0531+21 also compiled from *CGRO* data. This spectrum apparently has a cutoff in the GeV range, since pulses at 10^{11} eV have not been reliably reported. The line is a prediction based on an "outer gap" model of pulsar gamma-ray emission.

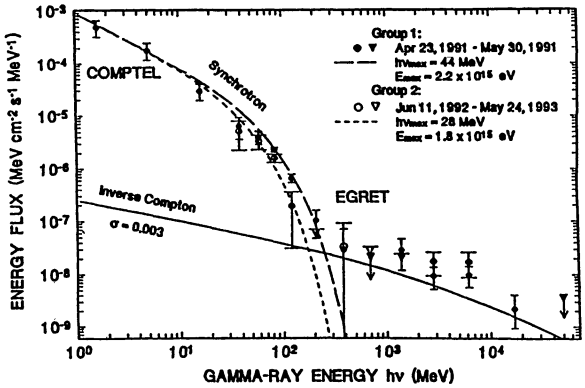

Fig. 10. Recent measurements primarily from the *CGRO* of the total Crab Nebula gamma-ray spectrum extend with a nearly unbroken power law from ~ 100 keV to beyond 1 GeV, and may connect with a point at 10^{11} eV obtained from observations of Air Cerenkow radiation

5.3. Unpulsed High Energy Spectrum

Measurements and upper limits obtained with HEAO–1 on the unpulsed spectrum of the Crab Nebula over the 15 keV to 11 MeV range confirmed previous indications of a "break" at a few 100's of keV in the power-law index of the extrapolated X-ray spectrum (Jung 1989). This, together with the flatter spectrum of the pulsar, shows that the pulsed emission dominates the steady flux at energies in the 100 MeV range. This was confirmed with measurements from the SAS–II (Thompson et al. 1977). The pulsed component does not extrapolate to TeV energies (Vacanti et al. 1991); it clearly cuts off in the GeV range.

Recent results on the unpulsed component obtained with the *CGRO* have been reported by De Jager et al. (1994). Figure 10 shows the unpulsed spectrum, which has a clear flattening above 30 MeV, that generally extrapolates to the TeV measurements (Vacanti et al. 1991). The extended spectrum is interpreted as Compton up-scattering by the relativistic electrons on the synchrotron photons (De Jager & Harding 1992) or by pair processes outside the light cylinder (Cheung & Cheng 1993).

6. SUMMARY

In this paper, I have presented a brief historical account of high energy phenomena from the Crab Nebula and its pulsar PSR 0531+21 from the view of an insider during the "discovery" days. These early observations have hopefully been placed in the context of recent results. The Crab continues to be a unique source of new phenomena, and after being regarded as a "high energy object" during most of the recent preceding decades, is now being given the attention it fully deserves from optical astronomers. The recent work is well complemented by observations from the Compton Gamma Ray Observatory, and by the renewed interest in theoretical work on plerionic systems.

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