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ANCIENT HISTORY AND RECENT DISCOVERIES

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B. B. Rossi

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B. B. Rossi

Center for Space Research
Massachusetts Institute of Technology
Cambridge, Massachusetts

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I.

The Chinese and Japanese chronicles for the year 1054 of the Christian era registered the sudden appearance in the constellation of Taurus of a new star - a "guest star" - of extraordinary brightness, which gradually faded away until some two years later, it was no longer visible.

Centuries went by, and hardly anyone was aware of this event when, in 1771, the French astronomer Messier compiled a catalogue of all known comet-like objects (nebulae and clusters) that appeared to occupy fixed positions in the sky. The first item on his list (M1) was a nebula in the constellation of Taurus, about 4 arc minutes across, whose existence had been known for about 40 years. During the following decades this nebula was observed repeatedly with improved telescopes. In 1848 the shape of the object suggested to the British astronomer Lord Ross the name of <u>Crab Nebula</u>, which has been since generally accepted.

The next event of crucial importance for the present story was the detection at a Baltic observatory, in 1885, of an exceedingly bright star in the Andromeda galaxy, that was the result of a sudden flare up. In the subsequent years, a number of similar stellar outbursts were observed in external galaxies. In some cases the brightness of the "new" star was comparable to or even greater than the total brightness of the galaxy before the outburst. By 1920, it had become generally accepted that these extraordinary outbursts were not limiting cases of ordinary novae, but were to be regarded as an entirely different class of astronomical events. Since the late thirties these events have been known as <u>supernovae</u>.

The discovery of supernovae in external galaxies stimulated the interest of astronomers in the historical records of events that might be interpreted as supernovae outbursts within our own galaxy, and prompted them to search for celestial objects that might be regarded as remnants of these outbursts. In the early twenties astronomers noticed the coincidence between the position of the Crab Nebula and the position of the "guest star" of 1054, as could be deduced from the descriptions contained in the oriental chronicles. They also discovered that the angular dimensions of the Crab Nebula were gradually increasing. Under the assumption that the nebula had originated from a point-like object and had undergone uniform expansion since its birth, it was possible to compute its age, which turned out to be close to the time elapsed since the appearance of the "guest star." On the basis of these results Hubble, in 1928, suggested that this event had been a supernova outburst, and that the Crab Nebula was its remnant.

In the following years the very powerful optical telescopes which by then had become available were applied to a systematic study of the Crab. It was found that this object consisted of an "amorphous mass", in which long and thin "filaments" were embedded. The light from the "amorphous mass" (which accounted for over 90 percent of the whole optical emission from the Crab) had a continuous featureless spectrum. In the light from the filaments, on the other hand, the lines of the known elements (especially the $H\alpha$ line of hydrogen) appeared prominently (see Fig. 1).

The spectral lines of individual filaments were observed to exhibit Doppler shifts, which were interpreted as due to the expansion of the nebula. From this effect, the radial component of the velocity of expansion was found to be a little over 1000 km/sec. This result together with the observed rate of increase of the angular radius (0.21 arc seconds per year) provided an estimate of 5000 light years for the distance of the Crab Nebula, under the assumption that the velocities of expansion along the line of sight and perpendicularly to it were identical. (However, it is now believed that the expansion may not be exactly isotropic, and consequently that the above estimate of the distance may be in error by some 20 percent, probably on the low side.)

In the meantime theoretical ideas pertinent to the supernova phenomenon began to emerge. Already in 1939 Oppenheimer and his collaborators addressed themselves to the problem of what happens when the nuclear fuel in the central part of a star is nearly exhausted, so that the pressure of the radiation generated by the nuclear reactions can no longer balance the forces of gravitational attraction. They found that, depending on its mass, the star will collapse either into a "white dwarf", or into a lump of nuclear matter, i.e., a "neutron star". According to present views, prior to the final collapse, part of the stellar mass is blown out into space, perhaps because of the sudden ignition of the remaining nuclear fuel. This outburst manifests itself as a supernova, and the ejected matter forms the cloud later found at the location of the outburst.

By then, astronomers had discovered two faint stars near the center of the Crab Nebula, and had suggested that either of them might be the residual condensed object of the supernova explosion of 1054. However, while one of these stars had an entirely "normal" spectrum, the other (known to the astronomers as the <u>south preceding star</u>) was found to have a featureless spectrum, quite different from the spectra of ordinary stars. Furthermore, for some time astronomers had been observing certain peculiar "ripples", which traveled through the cloud at enormous speed (about 1/10 the speed of light). Careful measurements showed that the vector velocities of these ripples were directed away from the south preceding star. For both these reasons Baade and Minkowsky in 1942 concluded that this object rather than the other member of the doublet should be identified as the supernova remnant.

II.

Astronomical research in the years following the end of the second world war was dominated by the almost explosive development of radio astronomy. One of the first discrete radio sources to be identified with an optical object was the Crab Nebula (Bolton et al., 1949).

The discovery of the radio emission of the Crab brought to a sharper focus the problem of the origin of the radiation from this object, which had puzzled astronomers for several years. Indeed, while it had been found very difficult to explain the shape and the intensity of the optical continuum in terms of thermal processes (the only celestial radiation processes well understood at the time), in no way could processes of this kind account for the strong radio signals.

The solution of the problem came in the early fifties when Shklovsky suggested that both the radio emission and the optical continuum were due to the same, non-thermal process, a process to be identified with the so-called synchrotron effect, i.e., the emission of electromagnetic radiation by highly relativistic electrons traveling in a magnetic field

(Shklovsky, 1953). Unlike thermal radiation, synchrotron radiation is linearly polarized. Although it was difficult to predict whether or not a polarization might actually be observable (since in the case of a source of finite dimensions the net effect depends on the degree of randomness of the magnetic field), Shklovsky's suggestion prompted astronomers to search for a polarization of the optical continuum of the Crab. The positive results of these observations, and the detection, some time later, of a similar polarization in the radio band of the spectrum, have been generally accepted as a crucial test of the synchrotron hypothesis. Today, of course, the synchrotron process is known to play a major role in many astrophysical phenomena. But it is worth noting that it was in the Crab Nebula that the occurrence of this process on a cosmic scale was first established.

Synchrotron emission extending into the optical band implies that the Crab Nebula is permeated by a magnetic field (of an estimated strength between 10^{-4} and 10^{-3} gauss) and contains electrons with energies extending up to at least 10^{12} eV. Various suggestions about the origin of these electrons were put forward (although none was worked out quantitatively into a theory). High energy electrons might have been left over from the original explosion; or they might be ejected continuously from the central star; or they might be accelerated while moving through the cloud by some sort of Fermi-type process.

Whatever mechanism was responsible for the acceleration of electrons, it was thought that the same mechanism would also accelerate protons and heavier nuclei. While the electrons lost their energy (or most of it) within the cloud by synchrotron emission, protons and heavier nuclei (for which synchrotron losses are negligible) would escape into interstellar space without appreciable energy loss, and would thus contribute to the galactic cosmic-ray flux. In fact, it was argued that all galactic cosmic rays may originate from supernovae, being produced primarily at the time of the initial outburst.

III.

In 1962, the discovery of surprisingly strong celestial sources of X-rays - including both localized sources and a diffuse background (Giacconi et al., 1962) - opened up the new field of X-ray astronomy. X-rays, of course, can only be observed at very high altitudes, because of their strong absorption in the atmosphere. Most of the results available to this date have been obtained by means of rockets, although balloons have made important contributions to the study of the "hard" component of the X-ray flux. The second X-ray rocket, flown in October 1962 (Gursky et al., 1963) already gave some tentative indication of an X-ray source in the general direction of the Crab Nebula. The following spring a rocket equipped with a detector of improved angular resolution established the existence of an X-ray source within a few degrees of the Crab (Bowyer et al., 1964a). The crucial proof that this source was indeed coincident with the Crab came in the summer of 1964 when a rocket flown during an eclipse of the Crab by the moon showed the simultaneous disappearance of the X-ray and of the optical flux (Bowyer et al., 1964b). The identification was confirmed in 1967 by means of a collimator of very fine angular resolution, which measured both angular coordinates of the X-ray source with a precision of about 20" (Oda et al., 1967).

The results of the 1964 and 1967 observations are summarized in Fig. 2. They agree in showing that, within the observational uncertainties, the center of the X-ray source is coincident with the center of the visible nebula. Moreover both experiments indicate that the X-ray source is not point-like, but has an angular diameter of about 100" (i.e., of the same order as that of the visible nebula, although perhaps somewhat smaller).

Since its discovery, the X-ray source in the Crab has been the object of many observations. In reporting the results of these observations, it may be instructive to compare them with those concerning another strong X-ray source, Sco X-1, which has also been extensively investigated. Unlike the Crab, Sco X-1 had not been recognized by the astronomers as a peculiar celestial object before its discovery as an X-ray emitter. Subsequently it was identified with a faint star of unusual spectral characteristics (Sandage <u>et</u> <u>al</u>., 1966). Again unlike the Crab, Sco X-1 appears point-like (to the limit of the resolution achieved so far) both in the optical and in the X-ray band.

The X-ray emission from the Crab, as well as its light emission, were found to be nearly constant in time, at least when averaged over periods of seconds (Sco X-1, on the contrary, was found to be highly variable both in the [illegible]y and in the optical bands).

In the X-ray band, the spectral function of the Crab (energy flux per unit interval of photon energy) was found to follow closely a power law with exponent close to unity from hν = 1 keV to hν = 100 keV. (The X-ray spectrum of Sco X-1 has a very different shape, being represented approximately by an exponential function, similar to that expected from a thermal, optically thin source at about 5 x 10^7 °K. This implies that the spectrum of Sco X-1 is much "softer" than that of the Crab; indeed, while Sco X-1 is about 10 times brighter than the Crab at photon energies of the order of 5 keV, the Crab becomes brighter than Sco X-1 at photon energies above about 30 keV.)

A log-log plot of measurements in the radio, visible, ultraviolet and X-ray bands suggests that the whole electromagnetic spectrum of the Crab may be described by a single smooth function. This has been taken as an argument in favor of a common origin (i.e., synchrotron radiation) for the entire spectrum. Although not yet definitely proven, the assumption of a synchrotron origin for X-ray spectrum of the Crab is accepted by most scientists, to a large extent because of the difficulty of finding a more likely alternative. The only other process that has been considered seriously is thermal radiation from a hot, optically thin plasma cloud. As already noted, if the cloud is at a uniform temperature, this process gives rise to an exponential spectrum, i.e., a spectrum more similar to that of Sco X-1 than to that of the Crab. Of course, if the plasma temperature varies from point to point, as it may well do in the Crab Nebula, the X-ray spectrum will be a sum of exponentials which might conceivably simulate a power law over a limited range of photon energies. However, beyond a photon energy corresponding to the temperature of the hottest region, the spectrum should drop sharply. Therefore the possibility of a thermal radiation process became increasingly remote as spectral measurements were extended to higher and higher energies and failed to detect any cut-off.

With the magnetic fields that supposedly exist in the Crab, synchrotron emission in the X-ray band requires electron energies of the order of 10^{14} ev. It is worth noting that for these very energetic electrons the synchrotron process is exceedingly effective. Consequently the electrons lose energy at a very fast rate, which appears to rule out the possibility that they might have originated from the initial explosion.

At this point it may be useful to quote some figures.

The X-ray flux from the Crab Nebula, in the spectral band from $h\nu = 1$ keV to $h\nu = 100$ keV, amounts to about 7×10^{-8} erg/cm^2 sec at the earth. Taking the distance of the Crab as 5000 l.y., its X-ray emission turns out to be about 2×10^{37} erg/sec, i.e., about 5000 times the total emission of the Sun in all wavelengths. The emission in the optical band is about 1/4 and the emission in the radio band ($\lambda > 3$ cm) is about 1/1000 of the X-ray emission. (For Sco X-1, the corresponding figures are about 1/1000 and about 2×10^{-8}.)

IV.

We now come to the very recent developments of astronomical research, and here again we find that the Crab Nebula occupies a central position in the new discoveries.

Early in 1968, Hewish and his co-workers announced the discovery of pulsating radio sources, or pulsars (Hewish et al., 1968). At the end of that year, some 25 pulsars were known, with periods ranging from about 2 sec. to about 1/30 of a second. Of these, only two had been identified with previously known celestial objects, both of them supernova remnants. One of them was Vela X (Large et al., 1968), the other was the Crab Nebula (Staelin et al., 1968). The pulsar in Vela X had a period of about 89 ms, that in the Crab (known also as NP 0532) had a period of about 33 ms, the shortest among all known pulsars.

The periods of the "slow" pulsars were found to be remarkably constant (for some of them it was established that the rate of change was less than one part in 10^8 per year). The periods of the "fast" pulsars in Vela X and the Crab, on the other hand, were found to increase very slowly. For the Crab, the rate of increase amounts to one part in 2400 per year.*

In January 1969 another important discovery took place, with the detection, in the Crab Nebula, of the first and thus far the only optical pulsar (Cooke _et_ _al_., 1969). The period of the optical pulsations was found to be exactly identical to that of the radio pulsations, which proved beyond any reasonable doubt that the radio and the optical pulsars were the same object (although, of course, the radiations belonging to the two spectral bands may come from different regions of this object). Precise determinations of its position showed that the pulsating star is the south preceding member of the doublet found near the center of the Crab (Lynds _et_ _al_., 1969), and thus confirmed unequivocally the previous tentative

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*In the case of Vela X, the gradual increase of the period was interrupted, between February 4 and March 3, 1969, by a sudden decrease of two parts in one million (Radhakrishnan _et_ _al_., 1969; Reichley _et_ _al_., 1969).

identification of this star as the condensed residue of the supernova explosion. A further dramatic verification of this result came from a series of photographs taken through the slots of a rotating disk, which showed that the brightness of the south preceding star changed periodically between a maximum and practically total extinction when the time between successive "open" intervals was nearly equal to the period of the pulsations (see Fig. 3).

Quite naturally, the discovery of the optical pulsar in the Crab suggested a search for a pulsating component in the X-ray emission of the same object. During the month of April 1969, two rockets provided with detectors sensitive to "soft" X-rays (photon energies of several keV) were launched for this purpose, the first by the NRL group (Fritz et al., 1969), the second by the MIT group (Bradt et al., 1969). Both experiments did, in fact, detect the expected pulsations with a period exactly equal to that of the radio and of the optical pulsations (33.099522 ms at the time of the MIT flight).

Finally, a recent analysis of balloon data obtained in 1967 revealed that also the "hard" X-ray flux of the Crab (photon energies greater than about 35 keV) contains a pulsating component (Fishman et al., 1969). A balloon flight carried out in May 1969 confirmed this result and provided quantitative information on the size and shape of the pulses (Floyd et al., 1969).

Examples of the pulse shapes observed in different spectral bands appear in Figs. 4 through 7. Shown in each case is the time dependence of the radiation flux during one period, averaged over a large number of periods.

One sees that, at all wavelengths, each pulse contains two peaks, separated by a time interval slightly less than one half period. In the optical and in the X-ray bands, the shape of the pulses appears to be quite constant. In the radio band, however, the pulse shape varies greatly from pulse to pulse, and even averaging over thousands of pulses does not result in a stable pattern. It has been pointed out that this instability may be due, at least in part, to refraction of radio waves, possibly in the ionized gases within the nebula itself (Sheuer, 1968; Slee _et al._, 1968). This interpretation is consistent with the observed stability of the optical and of the X-ray pulses because refraction effects decrease rapidly with decreasing wavelengths.

There is evidence that at all wavelengths the radiation level between the first and the second peak is somewhat higher than the radiation level after the second peak. We shall take the view that this lowest level of radiation represents the steady emission of the nebula. In other words we shall assume that the emission of the pulsar actually drops to zero during each period. (Stroboscopic pictures such as those shown in Fig. 3 tend to support this assumption, but do not prove that it is rigorously correct.) By taking the lowest radiation level as the zero line, we can then separate the pulsating component of the radiation originating from the pulsar, from the steady component originating from the nebula.

Observations show that the ratio between the power in the pulsating mode and the power in the steady mode varies by a very large factor over the spectrum. In the radio and in the optical bands this ratio amounts to only several parts in one thousand. In the "soft" X-ray band it reaches the value of about 9 percent and in the "hard" X-ray band it seems to be higher still. From these results and from the spectral data on the total emission of the Crab reported previously it follows that all but a minute fraction (perhaps less than one percent) of the radiation from the pulsar is in the form of X-rays. This object, then, may be properly described as an <u>X-ray pulsar</u>.

The pulses observed in the optical and the X-ray bands, while very different in their size relative to the steady component, have strikingly similar shapes. In both spectral bands, one of the two peaks observed during each period has a width of about 1.5 ms, and the other has a width of about 3.5 ms.* Within the experimental errors, the separation of

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*However, one should note that the observed width of the narrow X-ray peak is not much greater than the time resolution of the instrument.

the two peaks is the same (about 13.5 ms). In the experiment by Bradt and his co-workers (see Fig. 6) recording of time signals from the WWV radio station during the rocket flight made it possible to correlate the X-ray observations with optical observations carried out, within a few hours of the flight, at the McDonald Observatory and at the Palomar Observatory. It was thus shown that the narrow peaks in the X-ray and in the optical bands are simultaneous within 1 ms.

The great variability of the radio pulses denies the possibility of a detailed comparison of their shape with that of the optical and radio pulses. Furthermore, the wavelength dependent delay of the radio pulses due to dispersion in the interstellar medium makes it difficult to establish an exact time correlation between the radio peaks and the optical peaks. All one can say on the basis of published reports is that the peaks in the radio and optical bands are simultaneous, with an uncertainty of about 6 ms, due almost entirely to the interstellar dispersion (Conklin et al., 1969).

V.

A reliable theoretical interpretation of the observational data that have been described above is still lacking. From these data, however, there begins to emerge a model which, although tentative and incomplete, may be worth discussing.

When pulsars were first discovered, two different kinds of models were suggested to account for their equally-spaced signals; i.e., (a) vibrational models and (b) rotational models. The vibrating or rotating star was thought to be either (a) a white dwarf or (b) a neutron star. While it was difficult to discriminate between these various possibilities as long as only pulsars with periods of the order of a second were known, the discovery of pulsars with periods of less than 0.1 sec. practically eliminated all choices but one. Since the free oscillations of white dwarfs have periods considerably longer than 0.1 sec; since white dwarfs cannot rotate at 10 revolutions per second or more without being disrupted; since the free oscillations of a neutron star are believed to be rapidly damped through the production of gravitational waves, it became practically certain that pulsars (or at least the "fast" pulsars such as that in the Crab Nebula) were rotating neutron stars.

We can estimate the kinetic energy of rotation, E, of the pulsar in the Crab by assuming that its mass is of the order of one solar mass ($\sim 2 \times 10^{33}$g) and by taking the conventional value of 10 km for its radius. With the observed angular velocity of $2\pi \times 30 \approx 190$ sec^{-1} we obtain

$$E \approx 1.4 \times 10^{49} \text{ erg}$$

From this figure and from the observed rate of increase of the period it follows that the pulsar loses rotational energy at the rate

$$-\frac{dE}{dt} \approx 3.7 \times 10^{38} \text{ erg sec}^{-1}$$

From the data reported previously we may estimate the total energy of the electromagnetic radiation of all frequencies emitted by the Crab Nebula to be several times 10^{37} erg sec^{-1}. It seems likely that an amount of energy, perhaps of the same order of magnitude, may be spent by the Crab Nebula in the production of cosmic rays. Thus, within the large uncertainties of the present estimates, - dE/dt appears to be remarkably close to the total energy output of the Crab Nebula, which naturally suggests that this energy is supplied by the gradual slowing down of the rotating neutron star at the center of the Crab (Gold, 1969; Finzi *et al.*, 1969). An additional justification for accepting this suggestion as a working hypothesis in the formulation of our model may be found in the fact that previously it had been necessary to resort to *ad hoc* assumptions in order to account for the energy storage in the Crab Nebula.

It appears natural to interpret the pulsating signals received from a rotating object as due to a *light-house effect* (Gold, 1968). As another working hypothesis, we shall therefore assume that the electromagnetic radiation from a neutron star is confined to one or more narrow beams, which sweep past the observer as they corotate with the star. In the case of the Crab, there would be two such beams. The narrow principal peak requires a beam whose angular width in the direction perpendicular to axis of rotation is at most $2\pi/20$ (less if the axis of rotation is not perpendicular to the line of sight). If this beam were in the shape of a circular cone, the a priori probability of its being detected by an observer on the earth would be 5 percent or less. Thus it appears reasonable to assume that the beam responsible for the principal narrow peak, and, by inference, also the beam responsible for the secondary wider peak, are fan-shaped. In the simplest model, the median planes of the two "fans" are nearly, but not quite, at 180° to one another, and intersect along the axis of rotation of the pulsar. However, other geometries are compatible with the observations.

The emission of the radiation into discrete beams implies an azimuthal anisotropy in the structure of the pulsar with respect to its spin axis. The stability of the beams as observed in the visible and X-ray bands is more easily understandable if the anisotropy is due to a magnetization of the pulsar rather than to "hot spots" or other peculiarities in a plasma atmosphere of the pulsar, as had been suggested when only radio observations were available (Gold, 1968). It should be noted that the collapse of a star with a moderate magnetic field will, indeed, result in a neutron star with exceedingly large magnetization, even if only a minor fraction of the original magnetic flux is conserved. (For a star similar to the Sun, one hundred percent flux conservation would give rise to fields of the order of 10^9 gauss at the surface of the neutron star; field strengths up to 10^{13} gauss have been mentioned as a possibility.) It thus appears reasonable to further specify our model by assuming that the neutron star is strongly magnetized, and that the magnetization is not axially symmetric with respect to the spin axis.

We now come to the problem of the processes responsible for the steady component of the radiation (originating from the nebula) and of the pulsating component (originating from the neutron star). With regard to the former, as already noted, we know for sure that the continuous spectrum extending from the radio waves to the ultraviolet is due to a synchrotron effect, and we have good reasons to believe that the same effect is also responsible for the X-ray emission; which means that the nebula contains electrons with energies up to at least 10^{14} ev. According to our model, these electrons derive their energy from the kinetic energy of rotation of the neutron star. We may think of a direct process, whereby the electrons are accelerated by the strong time-varying electromagnetic field that exists in immediate neighborhood of the star, and are then injected into the surrounding magnetized plasma cloud. Alternately, we may think of an indirect acceleration mechanism; i.e., we may assume that the rotating neutron star loses energy to the cloud giving rise to disturbances (in the form of waves or shocks), which then, through a Fermi-type stochastic interaction with the electrons in the cloud, supply the energy radiated via the synchrotron process.

An analysis of the stochastic acceleration process (for example on the basis of a model based on the interaction between Alfvén waves and individual electrons; see Manley *et al.*, 1969) shows that the high efficiency needed to maintain the required electron spectrum can be achieved only under rather extreme circumstances. On the other hand, no quantitative treatment of the direct acceleration process has yet been developed. In this connection one should keep in mind that the electrons will lose energy by synchrotron radiation even as they are accelerated; and that the synchrotron losses are proportional to the square of the magnetic field and to the square of the energy. Therefore it is not easy to figure out how electrons can emerge from the region of strong magnetic field surrounding the neutron star with the enormous energy they need to radiate X-ray photons in the weak field of the nebula.

Let us consider next the pulsating component of the radiation. One may think of a variety of processes capable of generating pulsations in the long-wavelength band of the spectrum. The fundamental problem, however, is to explain the emission in the X-ray band which, by itself, accounts for at least 99 percent of the pulsating power, as already noted. In this portion of the spectrum, it appears that the only effective emission process is the interaction of electrons with the magnetic field. This process presupposes the existence around the neutron star of electrons with a suitable energy distribution. In the frame of reference corotating with the star, the spatial distribution of the electrons must be remarkably stable; i.e., the electron cloud must corotate rigidly with the star. Furthermore the distribution of the electrons in velocity space, and the pattern of magnetic field lines, must be such as to account for the assumed fan-shaped beams of the radiation.

Of course, rigid corotation can only occur up to a maximum distance of the spin axis where the rotational velocity becomes equal to the velocity of light (Gold, 1968). With an angular velocity of 190 sec^{-1}, this distance amounts to 1.6 x 10^8 cm. Note that, if the magnetic field resembles that of a dipole, and therefore varies as the inverse cube of the distance, its magnitude at the "light circle" in the equatorial plane is about 2.5 x 10^4 times smaller than at the surface of the neutron star.

Of course, electrons require a much smaller energy to radiate X-ray photons in the strong magnetic field surrounding the neutron star than they do in the weak magnetic field of the cloud. In this connection it is important to keep in mind that the motion of electrons in the plane perpendicular to the magnetic field is actually quantized (Chiu et al., 1969). In the subrelativistic region the energy levels are equidistant with a separation $\Delta\varepsilon = h\omega/2\pi$ where ω is the cyclotron frequency. With $\Delta\varepsilon$ measured in e.v. and the magnetic field in gauss, the following relation holds

$$\Delta\varepsilon = 1.16 \times 10^{-8} B$$

If $\Delta\varepsilon$ is very small compared with the photon energy, quantum effects are negligible and the interaction of the electrons with the magnetic field may be described by the classical theory of magnetic bremsstrahlung. In this case the average energy of the radiated photons is much smaller than the electron energy. If, however, $\Delta\varepsilon$ is close to the photon energy then the emission occurs via a process similar to an atomic quantum transition between two bound levels, and the energy of the emitted photons is equal to or a sizeable fraction of the electron energy. Even hard X-ray photons, then, may be produced by subrelativistic electrons.

Quantized emission in the X-ray band requires magnetic fields of the order of 10^{12} gauss or more. While these fields are not ruled out, it appears more likely to the writer that X-rays are produced in a region of lower magnetic field, in which case relativistic electrons are needed. One must then assume that electrons are first accelerated tc relativistic, but not necessarily extremely high energies, by the rotating neutron star. While in the vicinity of the star, they partake of its rotation and generate the pulsating component of the radiation. They then diffuse into the surrounding cloud, where, after perhaps gaining further energy, they give rise to the steady radiation.

VI.

To summarize, the model developed here pictures the Crab Nebula as a thin plasma cloud containing a weak magnetic field, with a fast-rotating strongly magnetized neutron star at its center. The magnetization of the star does not have axial symmetry with respect to the spin axis, so that the rotation gives rise to time-varying electromagnetic fields, which, in some way or another, are capable of accelerating electrons. For a while these electrons remain within the corotating magnetosphere of the neutron star, where they give rise to fan-shaped corotating beams of electromagnetic radiation. Subsequently they diffuse into the surrounding cloud, where perhaps they acquire further energy by a Fermi-type stochastic process. Synchrotron emission by these electrons in the weak magnetic field of the cloud gives rise to the steady flux of radiation.

Presumably the kinetic energy of rotation of the neutron star was initially derived from the conversion of some fraction of the gravitational energy released during the stellar collapse following the supernova explosion. From the time of its birth, the Crab Nebula has drawn from the rotating neutron star the energy needed to produce the various kinds of rays which it has been pouring out into space.

Whether or not the general features of this model will survive future observations and future theoretical discussions is still an open question. Here the model is presented as a working hypothesis, that may be useful in suggesting further lines of investigation. From the theoretical point of view, one of the basic problems in clearly a quantitative analysis of the possible mechanisms for the acceleration of the electrons. From the observational point of view, it would be desirable to examine the polarization of the X-ray emission in order to test the assumption that it originates from a synchrotron process. Furthermore it would be very illuminating to extend the observations of the steady and of the pulsating components of the electromagnetic spectrum to considerably higher photon energies. Finally we may hope that high-resolution X-ray pictures of the Crab, possibly taken at different wavelengths, will furnish important information on the mechanism responsible for the acceleration of electrons and help discover the region of space where this acceleration occurs.

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FIGURE CAPTIONS

Fig. 1 (a) Picture of the Crab Nebula in "white light" (taken through a polaroid filter), showing the diffuse luminosity.

(b) Picture of the Crab Nebula in Hα (taken through an interference filter), showing the filamentary structure (Mt. Wilson and Palomar Observatories).

Fig. 2 Observational results on the location and size of the X-ray source in the Crab Nebula, superimposed on a photograph of the nebula in ordinary light (from Oda _et al._, 1967). The data were obtained by Bowyer _et al._ (1964b) who observed the occultation of the Crab by the moon, and by Oda _et al._ (1967), using a modulation collimator. The arc marked "NRL 1964" shows the position of the moon's limb at the time when it crossed the center of the X-ray source, as given by Bowyer _et al._ The arc marked "NRL (Manley 1965)" shows the same data, corrected for the motion of the rocket during the experiment. The intersection of the "preroll" and "postroll" lines is the most likely position of the center of the source, as determined by Oda _et al._; the observational errors of this determination are also indicated. The dotted circle represents the approximated dimensions of the X-ray source.

Fig. 3 Stroboscopic pictures of the stars near the center of the Crab Nebula taken by J. S. Miller and E. J. Wampler at the Lick Observatory. The pulsar appears as the brightest object in the picture at the top; it is nearly invisible in the picture at the bottom. The change in the apparent brightness is due to the gradual phase change of the light pulses relative to the "open periods" of the stroboscopic disk (Lick Observatory photograph; see Miller et al., 1969).

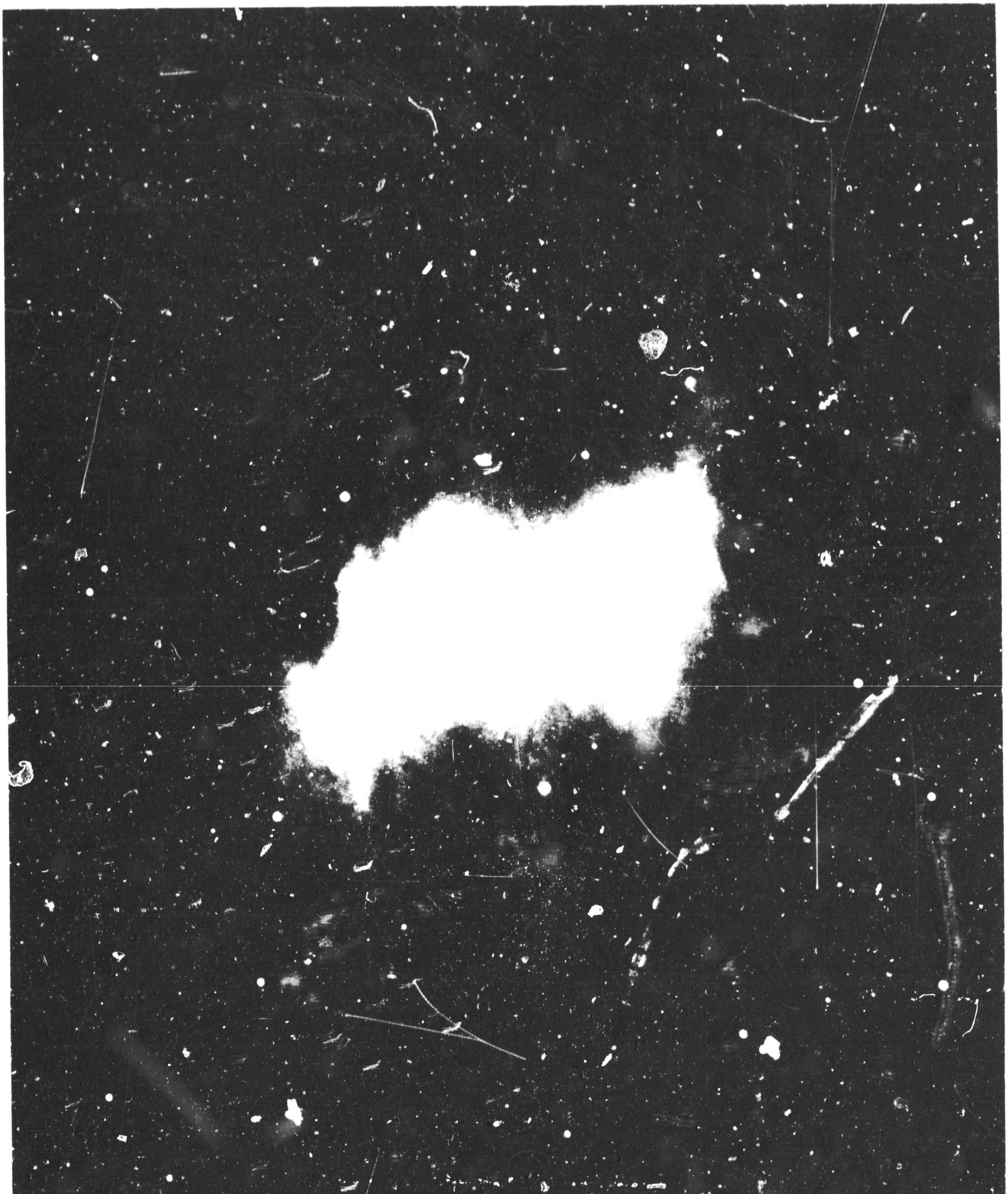
Fig. 4 Average pulse shapes of the pulsar in the Crab Nebula, as observed on three different days and at three different radio frequencies with the 1000-foot antenna at the Arecibo Ionospheric observatory; (a) Nov. 14, 1968; 196.5 MHz; 18,000 pulses. (b) Nov. 26, 1968; 198 MHz; 21,153 pulses. (c) Dec. 2, 1968; 430.0 MHz; 53,427 pulses. (From Comella et al., 1969).

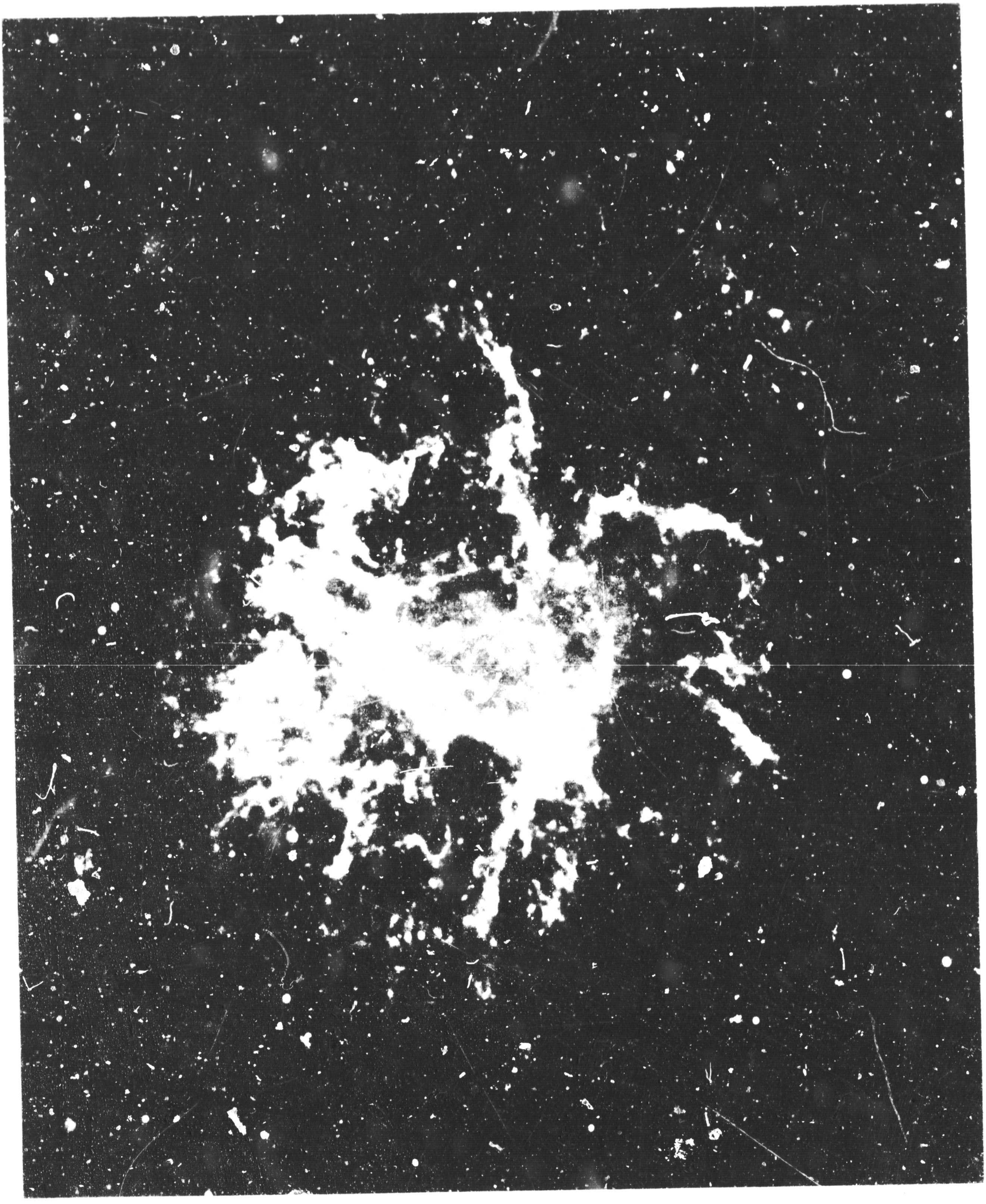
Fig. 5 Light curves for the Crab pulsar in white light. Curve (a): sum of 100,000 periods (b): sum of 30,000 periods, taken 3 1/2 hours earlier. The abscissa is channel number, each channel being of 100 microsecond duration; the left-hand scale refers to curve (a) and the right-hand scale to curve (b). (From Warner et al., 1969).

Fig. 6 (a) "Soft" X-ray data for the Crab pulsar obtained during 150 sec of the rocket flight carried out by Bradt and his co-workers on April 27, 1969. The detector was sensitive to photons in the energy range from 1.5 to 10 keV. Data were superimposed by dividing each period into 40 equal "bins" and distributing the counts into these bins. The intensities represented by the areas under peaks A and B are 4.5% and 4.6%, respectively, of the total X-ray intensity from the Crab.

Fig. 6 (b) Optical data shown in Fig. 5, integrated into 41 "bins" for comparison with the X-ray data (From Bradt et al., 1969).

Fig. 7 "Hard X-ray data for the Crab pulsar obtained during the balloon flight of May 10, 1969 by Floyd and his co-workers. The measurements cover the energy range from 25 to 100 keV. The data are divided into 30 "bins" (From Floyd et al., 1969).





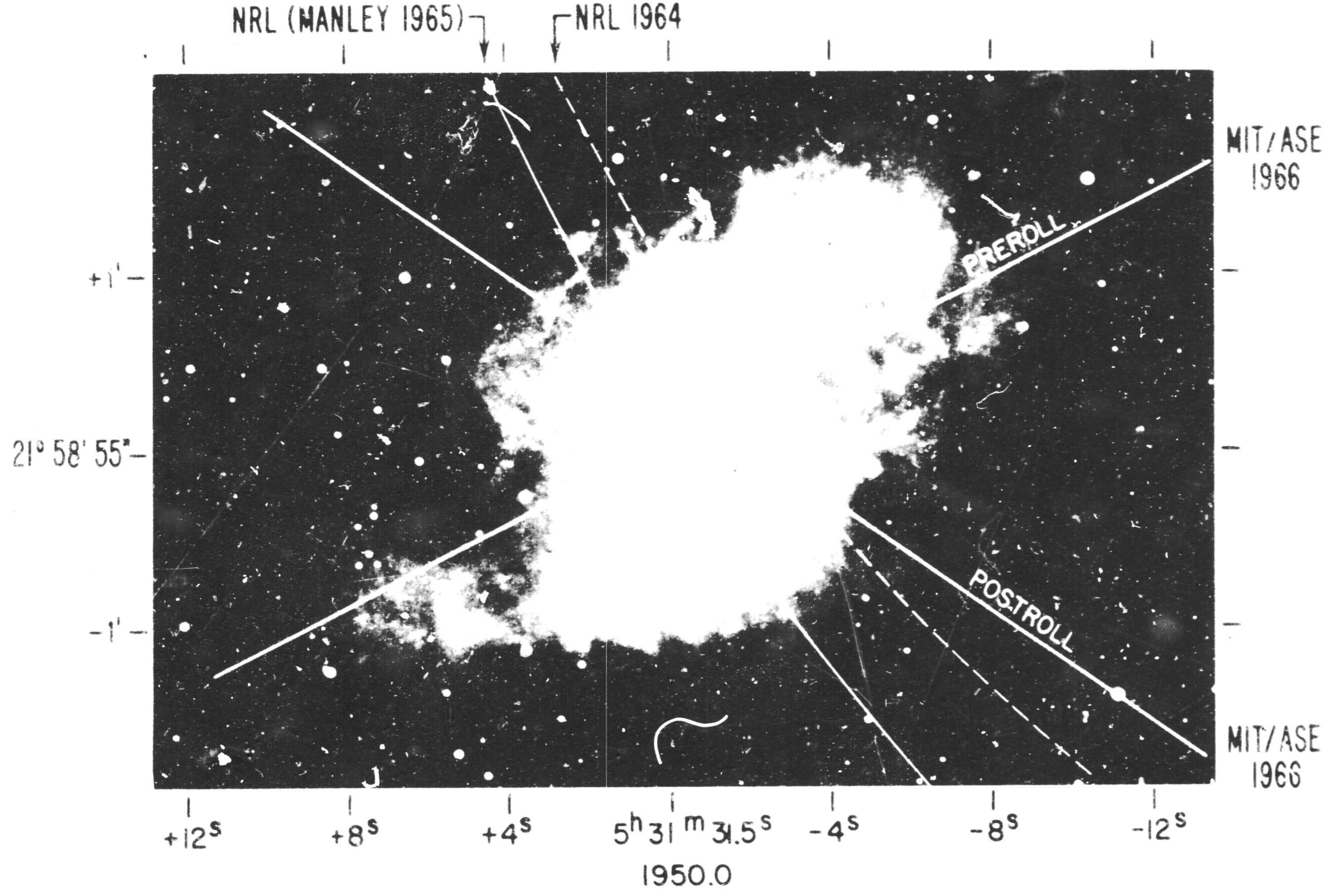

NRL (MANLEY 1965)
NRL 1964
MIT/ASE 1966
PREROLL
POSTROLL
MIT/ASE 1966
+1'
21° 58' 55"
-1'
+12s
+8s
+4s
5h 31m 31.5s
-4s
-8s
-12s
1950.0

Fig. 2

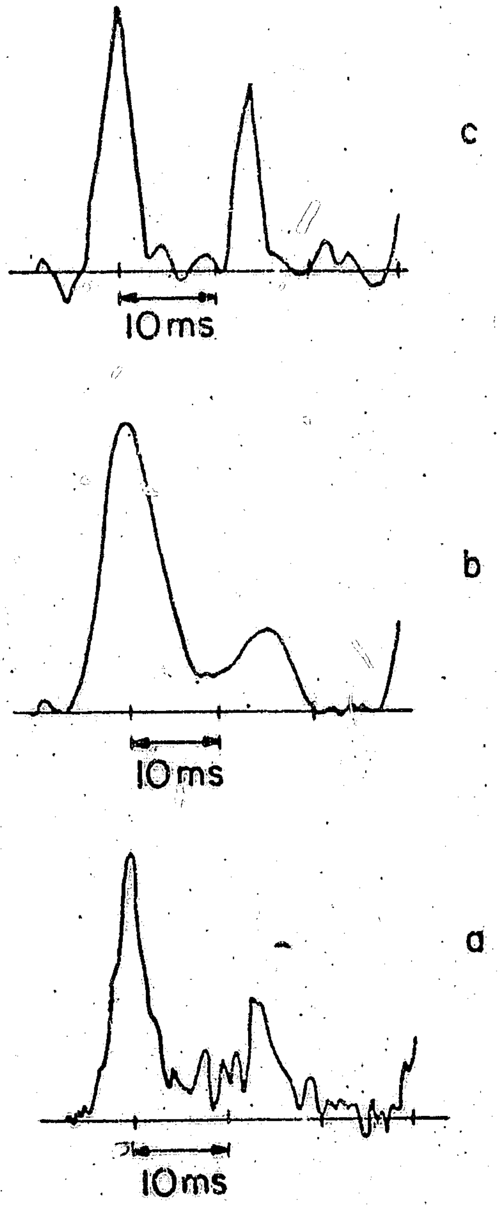
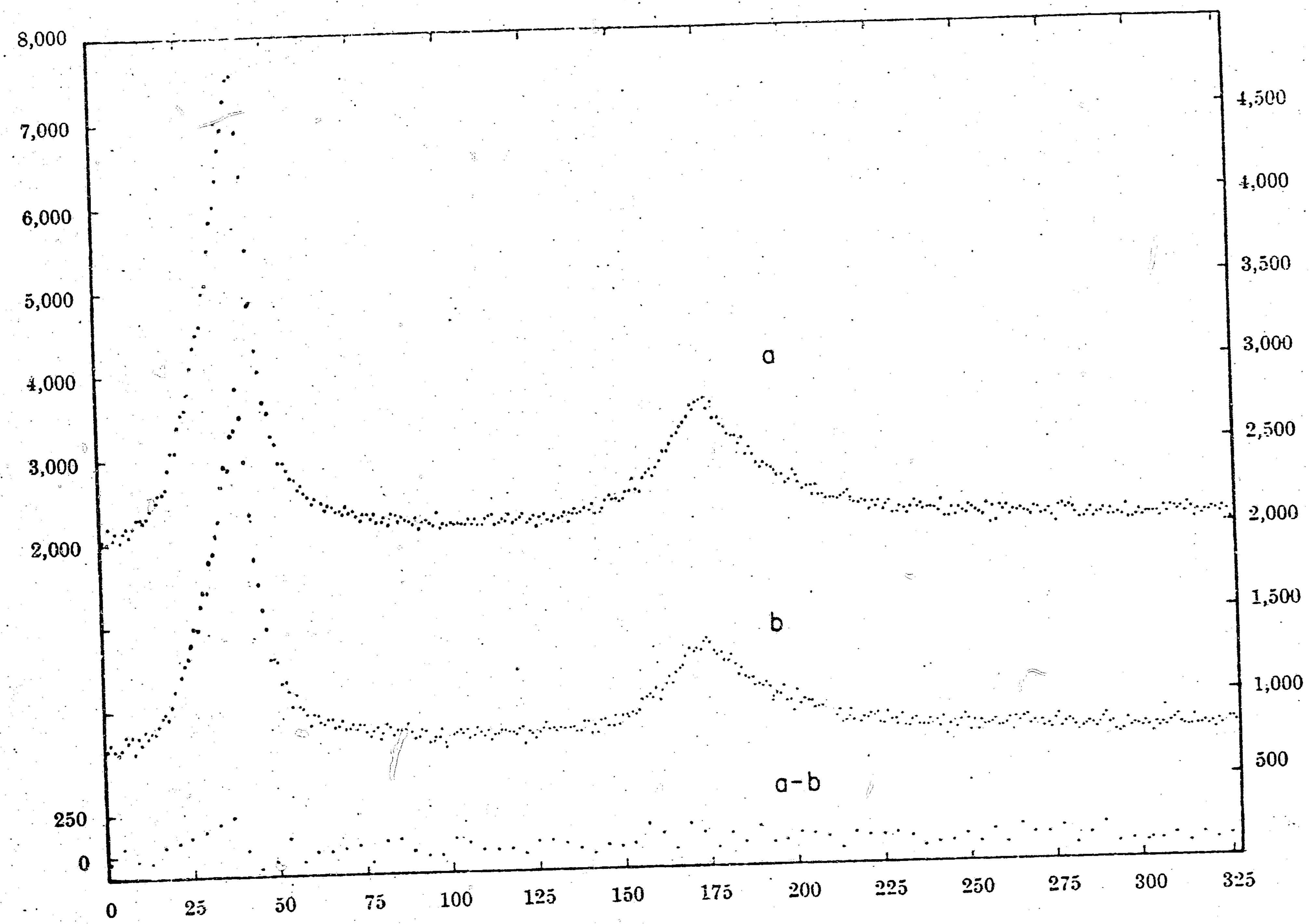


Fig. 4


8,000
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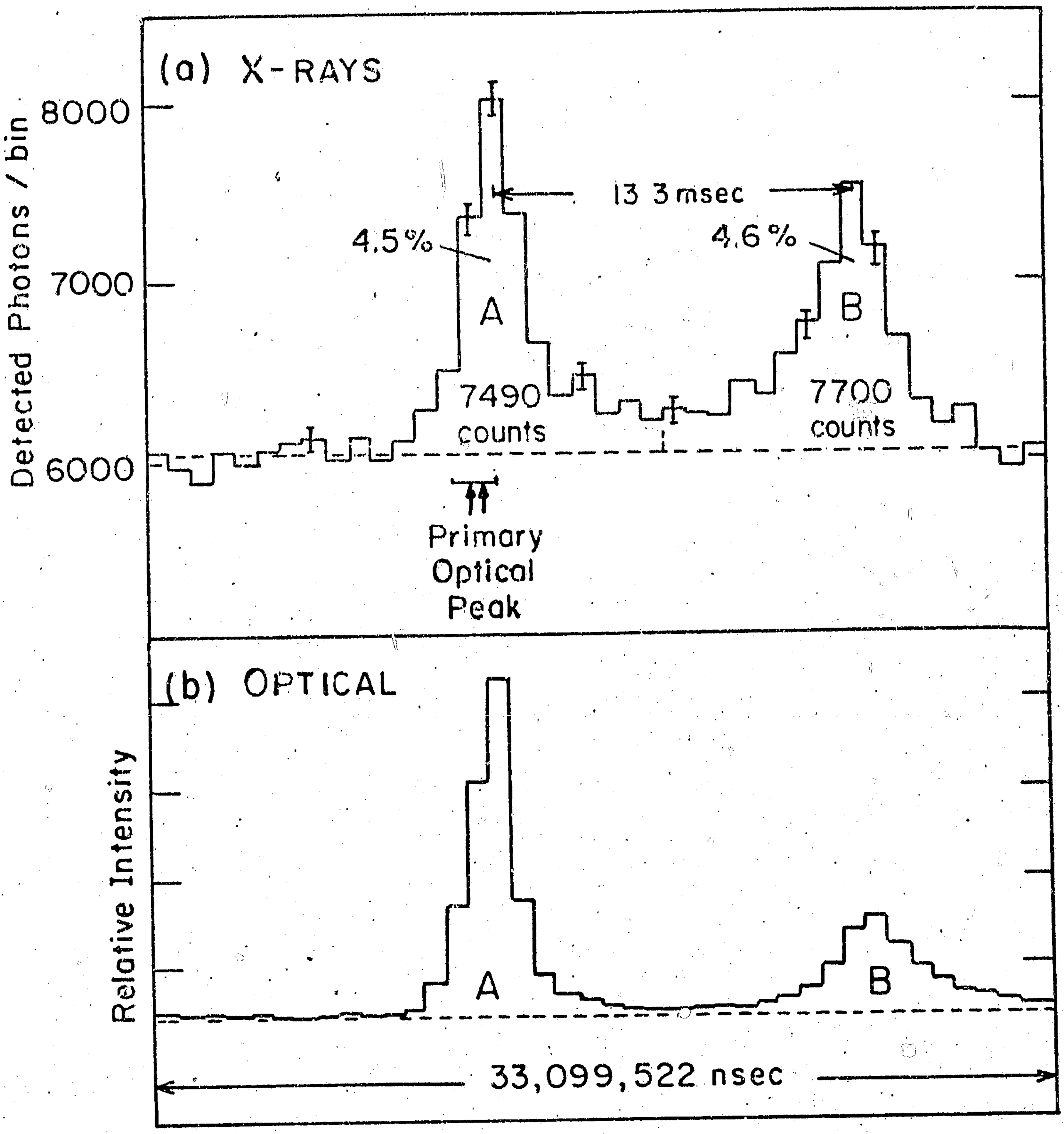
2,500
2,000
1,500
1,000
500
a
b
a-b
0
25
50
75
100
125
150
175
200
225
250
275
300
325

Fig. 5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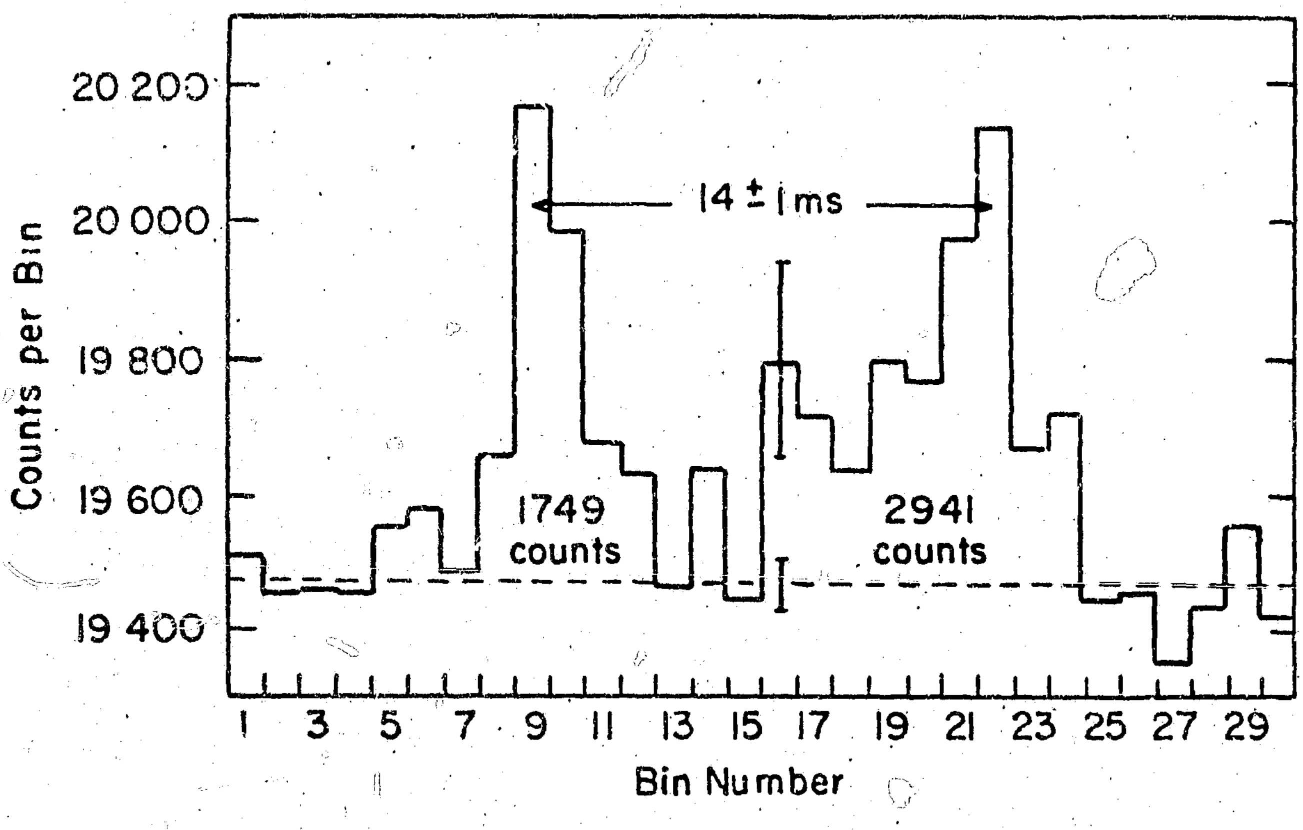
Detected Photons / bin
8000
7000
6000
13.3 msec
4.5%
4.6%
A
B
7490
counts
7700
counts
Primary
Optical
Peak
(b) OPTICAL
Relative Intensity
A
B
33,099,522 nsec

Fig. 6



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19 800
19 600
19 400
Counts per Bin
14 ± 1 ms
1749 counts
2941 counts
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
Bin Number

Fig. 7