The Crab Nebula

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The current knowledge about the Crab Nebula, the remnant of the supernova of 1054 AD, is reviewed. Relativistic electrons and positrons are accelerated over a broad range of energies by the pulsar in the Nebula; they radiate synchrotron radiation in the magnetic fields generated by the rotation of the pulsar. It is unlikely, however, that the Nebula can be a relevant source of cosmic rays. The shell of thermal gas around the Nebula is composed mainly of helium.

'In the first year of the period Chih-ho (1054), the 5th moon, the day chi-ch'ou (July 4) (a guest star) appeared approximately several inches south-east of T'ien-kuan (ζ Tauri). After more than a year it gradually became invisible.'

Thus the Chinese Annals[1] announce the supernova of the year 1054 AD, which left one of the most remarkable objects in the sky, the Crab Nebula, which radiates observable emission from the longest observable wavelengths (< 10 MHz) to gamma rays with $>10^{12}$ eV energy—a range of a factor of 10^{20} in photon energy. It is now clear that over much of this range the main process responsible for the emission is synchrotron radiation, due to energetic electrons and positrons gyrating in a magnetic field.

The Crab Nebula is believed to have been discovered by John Bevis. It was first catalogued by Messier (M1). It was named and described by the Earl of Rosse, who observed it in the middle of the last century with his six-foot telescope in Ireland. Extensive studies by Lampland[2] at Flagstaff rather convincingly revealed changes in the Nebula—although the difficulty in observations of this type is put in evidence by his finding of variations in the Sc galaxy NGC 4254 which appear not to have been confirmed. Slipher[3] obtained spectra, which revealed a continuum with superimposed emission lines split into two components; this reminded him of the Stark effect, but was later interpreted as due to expansion. Lundmark[4] in a list of suspected novae includes the 'guest star' of 1054 from the list by Ma Tuan Lin translated by Biot[5], and makes the brief comment 'near NGC 1952' (the Crab Nebula).

The evidence for variations in the Nebula was confirmed by Duncan[6], who found that it had expanded (in radius) by about 1.5 arcseconds in eleven years, corresponding to an age of the order of 900 years, and Hubble[7] noted that this made the identification with the star of 1054 more probable.

Subsequent milestones in the history of the Crab Nebula are the discovery of radio emission[8] (1949), polarization of the optical continuum[9] (1954), X-ray emission[10] (1963) and of the central rotating neutron star (pulsar) at radio[11], optical[12] and X-ray wavelengths[13] (1968–69). Since many phenomena have been seen and understood for the first time in the Crab Nebula, its properties have very much influenced the thinking about high energy phenomena in astrophysics. However, it should be stressed that it is in many ways an anomalous object; very few supernova remnants 'look' like the Crab Nebula.

Synchrotron radiation from the Nebula

Optical spectra of the Nebula show a strong smooth continuum superimposed on which there are emission lines due to the expanding filamentary shell which surrounds the Nebula. The radio and X-ray spectra both appear to be a smooth continuum. Interstellar dust absorbs the optical radiation and absorbing most strongly in the blue affects the spectral distribution. Correcting as well as possible for its effects, we see that the pieces of the spectrum fit together very well and that the overall spectrum[14] of the Nebula may be represented as a set of power laws with gradually increasing steepness towards the higher frequencies (Figure 1).

The continuum radiation is polarized. Overall the degree of polarization is of the order of 10% at the higher radio frequencies, in the visible and in X-rays. Locally values of more than 50% are measured. At the longer radio wavelengths, differential Faraday rotation in the Nebular shell and in the interstellar medium becomes important and reduces the overall polarization.

Both the polarization and the wide frequency range of the Nebular continuous emission exclude thermal mechanisms. Everything, in fact, points to the radiation being synchrotron radiation, emitted when relativistic electrons or positrons spiral in magnetic fields. A single electron with energy E(GeV) in a magnetic field B(Gauss) emits most of its energy in a broad frequency range centered on a critical frequency ν_c(Hz) given by

$$\nu_c = 1.6 \times 10^{13} E^2 B \sin\theta, \quad (1)$$

with θ the angle between B and the velocity vector of

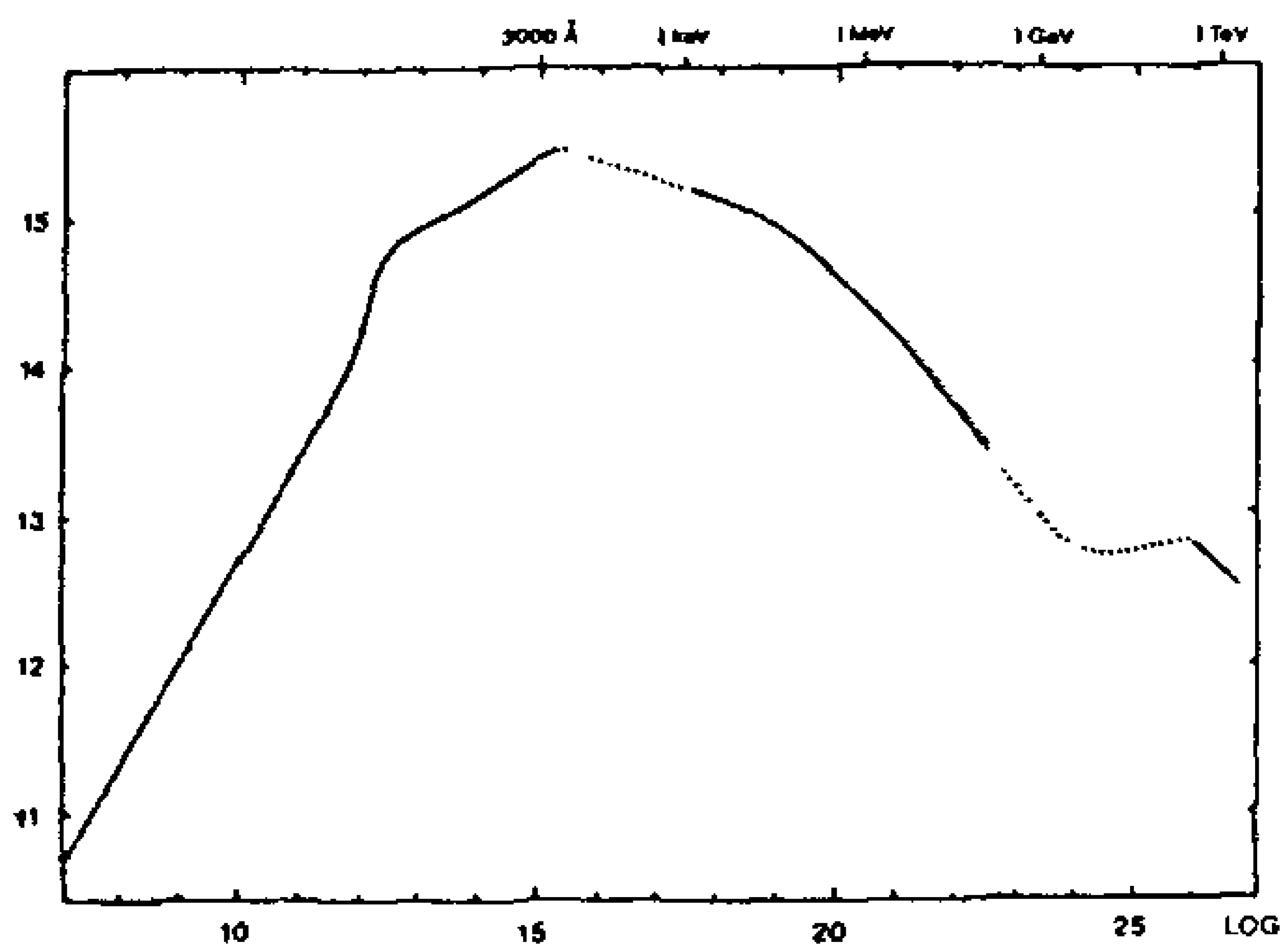

Figure 1. The spectrum of the Crab Nebula. The ordinate gives the quantity $\log[\nu F(\nu)]$ with $F(\nu)$ in Jansky (10^{-26} W m^{-2} Hz^{-1}), which is about equal to the energy received within an interval of $\log \nu$ of 0.4 centered on ν. At radio frequencies $F(\nu) \propto \nu^{-0.3}$, at visible wavelengths $F(\nu) \propto \nu^{-0.7}$ to $\nu^{-0.8}$ and at X-ray wavelengths $F(\nu) \propto \nu^{-1.1}$ gradually steepening to $\nu^{-1.4}$. The infrared bump around $\log \nu = 12.5$ is probably due to the radiation from dust in the filaments around the Nebula, heated by absorption of more energetic photons. The TeV photons are due to the inverse Compton process, the interaction of energetic electrons with optical photons in the Nebula. The dotted lines are interpolations based on the simplest possible fit in the ultraviolet, where interstellar absorption prevents observation, and on theoretical models[16] for the inverse Compton process below 0.1 TeV, where no instruments with sufficient sensitivity are available.

the electron. We shall see later that B is of the order of 1 mG. The frequency range of 10^7–10^{20} Hz (radio-100 keV X-rays) therefore corresponds to electrons with energies in the range of 10^{-1}–10^5 GeV. The electrons lose energy by radiating, and the time in which half of the energy is lost may be written as

$$t_{1/2} = \frac{0.084}{E B^2 \sin^2 \theta} = \frac{3.4 \times 10^4}{B^{3/2} \nu_c^{1/2} \sin^{3/2} \theta} \text{ years.} \qquad (2)$$

Taking again $B = 1$ mG we find for $t_{1/2}$ values in the range 10^5–10^{-1} years. Hence, it is rather clear that the higher energy electrons must have been accelerated recently and cannot be a relic from the supernova explosion 939 years ago. Taking into account also the adiabatic losses due to the expansion of the Nebula, this conclusion may be extended to all relativistic electrons.

Non-thermal acceleration processes frequently generate relativistic particles with a power law spectrum (as in the case of cosmic rays). If the differential energy spectrum of the electrons $n(E)$ is of the form $n(E) \propto E^{-\beta}$, the emitted synchrotron radiation will have the form $F_\nu \propto \nu^{-\alpha}$, with $\alpha = 1/2(\beta\text{-}1)$, at least for frequencies sufficiently far from the values of ν_c corresponding to the endpoints of the power law energy spectrum. Hence, the segments of the spectrum in Figure 1, which have a power law appearance, correspond to relativistic electrons with a power law energy spectrum, with $\beta = 1.6$ for the electrons radiating at radio wavelengths and up to $\beta = 3.8$ at much higher energies.

Imaging studies show the Nebula to be quite extended from the radio to the X-ray domain with the central concentration increasing with photon energy. The mean full width at half intensity of the Nebular images is 200 arcsec at 5 GHz, 100" at visible and 70" at 50 keV X-ray frequencies. This is undoubtedly related to the more limited lifetime of the electrons radiating at higher frequencies. Nothing is known about the extent of the 100 MeV gamma ray image, but it is likely to be very small if synchrotron radiation is responsible.

Observations[15] of Cerenkov radiation emitted by air showers generated by energetic photons from the direction of the Crab Nebula have yielded a determination of the spectrum at TeV photon energies. Photon emission at these high energies due to the Compton effect had, in fact, been predicted[16]. The synchrotron photons emitted in the Nebula may occasionally be scattered by the relativistic electrons present, with the energy gain of the photon a factor of order $(E/m_e c^2)^2$. Scattering of optical photons by electrons with 1000 GeV energy then yields TeV photons. If the observed TeV flux is, indeed, exclusively due to this process, the number of electrons may be evaluated and this in combination with the observed synchrotron flux yields the mean magnetic field strength. A careful modelling leads to a mean value of about 0.3 mG in the relevant parts of the Nebula. This magnetic field is generated by the rotation of the pulsars, but the detailed electrodynamics are still far from clear.

In a very general way the spectrum of the Nebula may perhaps be understood. Suppose electrons with an energy spectrum $E^{-\beta}$ are injected into the Nebula. If the injection is continuous, the electrons found in the Nebula will have the same spectrum up to the energy where energy losses become important during the time electrons have been injected. It is easily seen that at higher energy the spectrum becomes $E^{-(\beta+1)}$. Hence, we would expect[17] an initial synchrotron spectrum with index α to have a break above which the index would be $\alpha + 0.5$. Suppose now the injection is episodic. If there is no current injection, only electrons which have not lost too much of their energy since the last injection will still be found and at a given energy these are the electrons with $\sin\theta$ sufficiently small. If under the circumstances we evaluate the synchrotron spectrum we find that the index now is $4/3\,\alpha + 1$. Hence, if we inject electrons corresponding to $\alpha_0 = 0.3$, we could understand $\alpha = 0.8$ followed by $\alpha = 1.4$ at higher frequencies and this is, in fact, the global spectrum of the Nebula. Moreover, the first break occurs about where the lifetime of the electrons is of the order of a thousand years. The physical mechanism for such episodic injection is obscure.

It is not clear that such a simple picture is sufficient. In a recent study the optical spectral indices have been mapped in much detail[14]. A very large variation is found with the indices being at least 0.4 larger in the outer parts than further in (Figure 2). Since the radio spectral index is everywhere about the same ($\alpha=0.3$), it follows that the $\alpha_0+0.5$ spectrum is a gross oversimplification. Apparently the relativistic electron spectrum is quite inhomogeneous through the Nebula, with only limited mixing of electrons accelerated long ago and more recently. Very accurate images in radio, IR, optical and X-ray wavelengths will be needed to make further progress.

Whatever the details, it is clear that a quasi-continuous input of relativistic electrons is needed to keep the Nebula shining at higher frequencies. The discovery of the central pulsar has at least clarified the source of energy for this. A pulsar is a rotating, magnetized neutron star. Having measured both the rotation period and its time derivative, we may determine the loss of rotational energy provided the moment of inertia is known. For representative parameters the energy loss of the pulsar is around 5×10^{38} ergs. The total synchrotron radiation emitted by the Nebula is about 20% of this and so there is no energetic problem. Exactly how the relativistic electrons are accelerated and what determines their energy spectrum are still totally unclear.

There are at the moment some 5×10^{49} relativistic electrons with $E>0.1$ GeV in the Nebula. If they have been injected over 939 years and if none has escaped, the average injection rate must have been 2×10^{39} electrons and positrons. The most likely origin of these is in showers of electron pairs and gammas in the pulsar magnetosphere. Some of the electrons and positrons will escape into the Nebula, but others will fall on the surface of the neutron star, with the precise amounts depending on the details of the magnetic field structure. The positrons will annihilate and generate 511 keV gammas. Recent observations[18] have shown a flux of gamma rays at about 440 keV corresponding to the order of 10^{39} positrons, the lower energy then being due to the gravitational redshift for plausible neutron star models, which corresponds well to the number of relativistic positrons expected in the Nebula. While this agreement is suggestive, it should be noted that these observations would need confirmation. Moreover, in some other observations of the Crab Nebula gammas have again been seen, but at 560 keV. If confirmed, this would indicate a much more complex mechanism, presumably involving rapid motion of the annihilating positrons. Current and future satellite-based detectors should clarify the situation by obtaining data with adequate sensitivity to determine what is real and what not.

Dynamics of the Nebula

A rotating magnet in a vacuum generates electromagnetic waves. In the presence of charged particles the situation becomes more complex. In typical pulsar models at certain points strong electric fields build up which may lead to discharges in which energetic electrons are produced which, in turn, emit gammas and start e^+e^- cascade. At the same time the electrical currents produce a magnetic field in the Nebula.

As we have seen, the Crab pulsar currently puts its rotational energy into the Nebula at the rate of about 5×10^{38} ergs s^{-1} corresponding to 1.5×10^{49} ergs over the last 939 years if the rate were constant. The mean radius of the Nebula is around 4 light years, and the mean energy density would be 6×10^{-8} ergs cm^{-3}. If half of this were in the form of magnetic field energy ($B^2/8\pi$ cm^{-3}) the magnetic field strength would be 0.9 mG. Of course, this estimate neglects the fact that the pulsar produced more energy in the past and that magnetic energy has been lost in the expansion of the Nebula. Nevertheless, it shows that the pulsar parameters are adequate to explain the Nebula.

If only relativistic electrons and magnetic fields were present in the Nebula it would expand at relativistic speeds. The inertia of the shell of filaments around the Nebula prevents this. It was discovered by Baade[19] that the shell is in accelerated expansion. The average velocity over the last 939 years is about 10% less than the present day velocity. With a present velocity of 1500 km s^{-1} we then find a mean acceleration of 10^{-3} cm s^{-2}. As first suggested by Pikelner[20] the acceleration of the shell is undoubtedly due to the pressure of relativistic gas and magnetic fields. Its equation of motion may be written as

$$m\ddot{R}=\frac{1}{3}(B^2/8\pi+\varepsilon_{cR}), \tag{3}$$

where m is the mass of the shell per cm^2 and ε_{cR} the total energy density in relativistic particles. As discussed later, the mass of the shell is uncertain but should be of the order of a few times the mass of the sun. If we were to take $2M_\odot$ we would have 2×10^{-5} g cm^{-2} for the mass per cm^{-2} and with the energy density of 6×10^{-8} ergs cm^{-3} found before the equality would hold. Again a proper integration over the history of the Nebula is required, but the results show that our picture is qualitatively reasonable. An important consequence follows.

Equation (3) may be used to determine the total energy in the Nebula without reference to pulsar energetics. At the same time, the requirement that the Nebula produce the observed amount of synchrotron radiation gives a relation between B and the energy density in relativistic electrons and positrons, which may be shown to be of the form $\varepsilon_{e\pm} \propto B^{-3/2}$. Suppose now B is very much smaller than we have assumed. Then the total energy density would have to be very large; similarly if ε_e were very small, B and therefore the total energy density would be large. The observed acceleration and the observed synchrotron emission may only be obtained simultaneously if conditions are not too far from equipartition between the energies in magnetic fields and in relativistic electrons or positrons. The same argument excludes that there is a much larger energy in the form of relativistic protons or heavier nuclei in the Crab Nebula than in electrons and positrons. Consequently, the Crab Nebula cannot be the type of object responsible for the cosmic radiation observed on earth in which the ratio between the energies of nuclei and electrons is nearly a factor of 100, and in which positrons are still rarer. It is ironic that the first source in which the presence of relativistic particles with a power law type energy spectrum was documented and in which the composition could have been expected to be enriched in heavy elements, is the only object which has definitely been shown not to be a source of cosmic rays. If the Crab Nebula pulsar is not a very exceptional pulsar, this would indicate in general that pulsars are not an important source of cosmic rays. Perhaps these are predominantly accelerated in shocks—perhaps in the interstellar medium. In fact, some recent observations of Cobalt in cosmic rays very tentatively suggest[21] that more than 10^5 years must have elapsed between supernova type nucleogenesis and the acceleration of the nuclei. The Co isotopes in question are formed by e capture from progenitor nuclei; immediate acceleration would have led to stripping of the electrons and would have put an end to the capture process.

The filamentary shell

A thick expanding shell of filaments surrounds and partly pervades the region of continuum emission (Figure 3). By comparing the angular displacements of the filaments on the sky with their radial velocities determined from Doppler shifts we may determine the distance even though the non-sphericity of the shell introduces some uncertainty. A distance of 6000 light years has generally been adopted, but the uncertainty remains large ($\pm 50\%$).

The filaments are composed of gas at a temperature of the order of 10^4 K and with electron densities of the order of 10^3 cm^{-3}. Their emission spectra show lines due to various ionization stages of H, He, C, N, O, Ne, Ar, S, Fe, Ni and perhaps other elements[22]. The principal source of ionization is the ultraviolet synchrotron continuum of the Nebula. Since the stronger filaments are optically thick in much of the ionizing radiation detailed models are needed. Generally such models are constructed on the basis of pressure equilibrium between regions of different ionization, but the possible effects of magnetic fields make the validity of this assumption uncertain. It could perhaps be expected that the filaments would have dense, cool, largely unionized cores, surrounded by hotter, ionized gas. Since much of the emission comes from the latter, there remains much uncertainty in estimates of the mass of gas in the dense cores. Typical estimates of the total mass of the filamentary shell are of the order of one solar mass or somewhat more.

The composition of the filaments appears to be remarkably normal as far as the fraction of nucleons contained in elements heavier than He and the relative abundances of these. However, the ratio of helium to hydrogen is a factor of at least three higher than in the sun and 'normal' stars. In fact, most of the mass of the filaments consists of helium.

Models of supernova explosions generally do not produce so much helium, but rather heavier elements and significant overabundances of N, O, S, Ar and Fe have been observed in supernova remnants. There is, however, a small mass range (around 9 solar masses for the original star) where models[23] show that much helium may be synthesized. Stars with still lower masses do not explode as supernovae, but after losing mass in a stellar wind turn into white dwarfs. Under certain rare circumstances the white dwarfs may explode (supernovae of type I), but then most of the star is converted into iron group elements.

If, in fact, the Crab Nebula progenitor had originally 9 solar masses, the question is what has happened to that mass. About 1 solar mass may be in the neutron star, another in the filamentary shell. The rest would then be either in dense cold cores of some filaments or outside the filamentary shell. The latter is not so improbable since the supernova explosion is likely to have been preceded by a mass loss phase. The lost mass would presumably be ionized by the continuum of the Nebula and, therefore, could well be observable. Searches have been made at radio, optical and X-ray wavelengths for a faint 'halo' around the Nebula, but no firm detection has been made. Especially at optical wavelengths present day instruments should allow the detection limits to be pushed down further.

The 'Jet'

Deep imaging of the Nebula reveals a curious feature, the 'Jet' (Figure 4). The Jet[24] appears to be a hollow

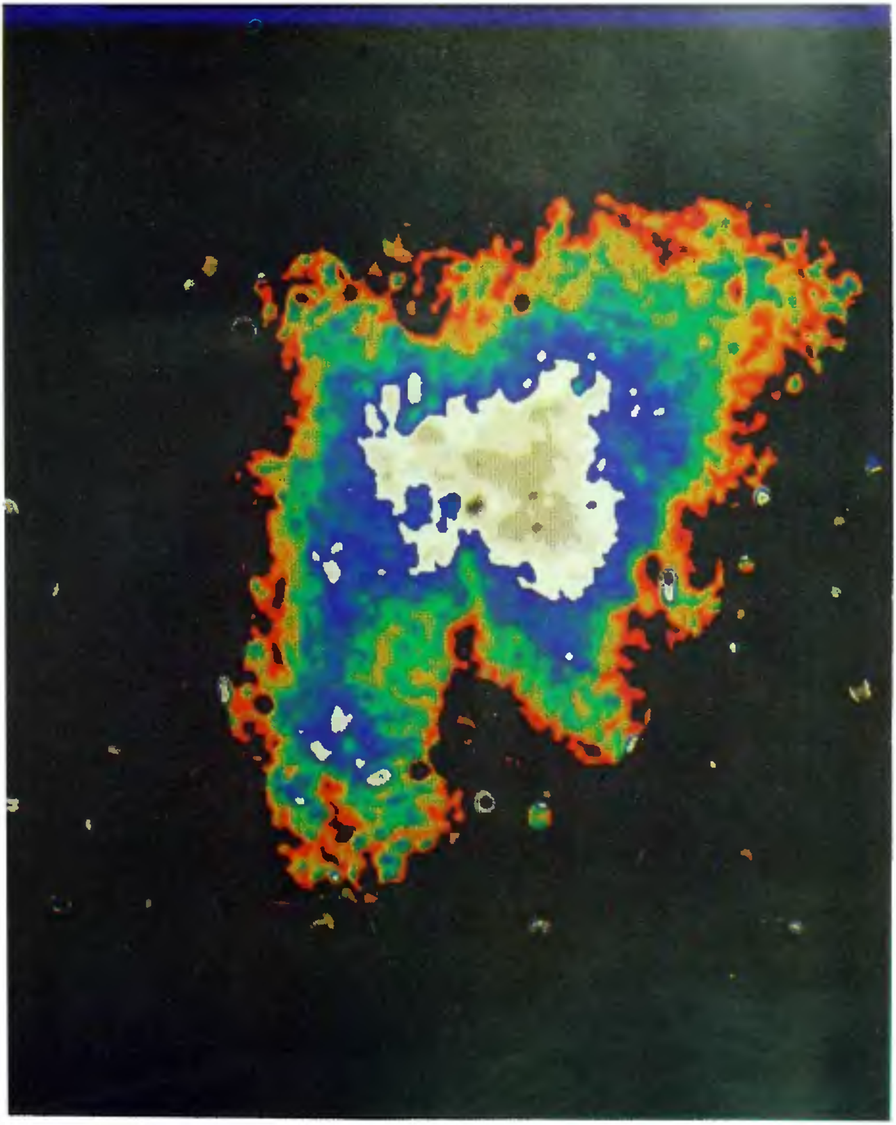

Figure 2. The distribution of optical spectral indices $\alpha\,[F(\nu) \propto \nu^{-\alpha}]$ over the Crab Nebula as determined by Véron-Cetty and Woltjer[14]. In the red part values of α are above 1.00, while in the grey area NW of the pulsar (indicated by a dot) values as low as 0.57 are reached.

The Crab Nebula

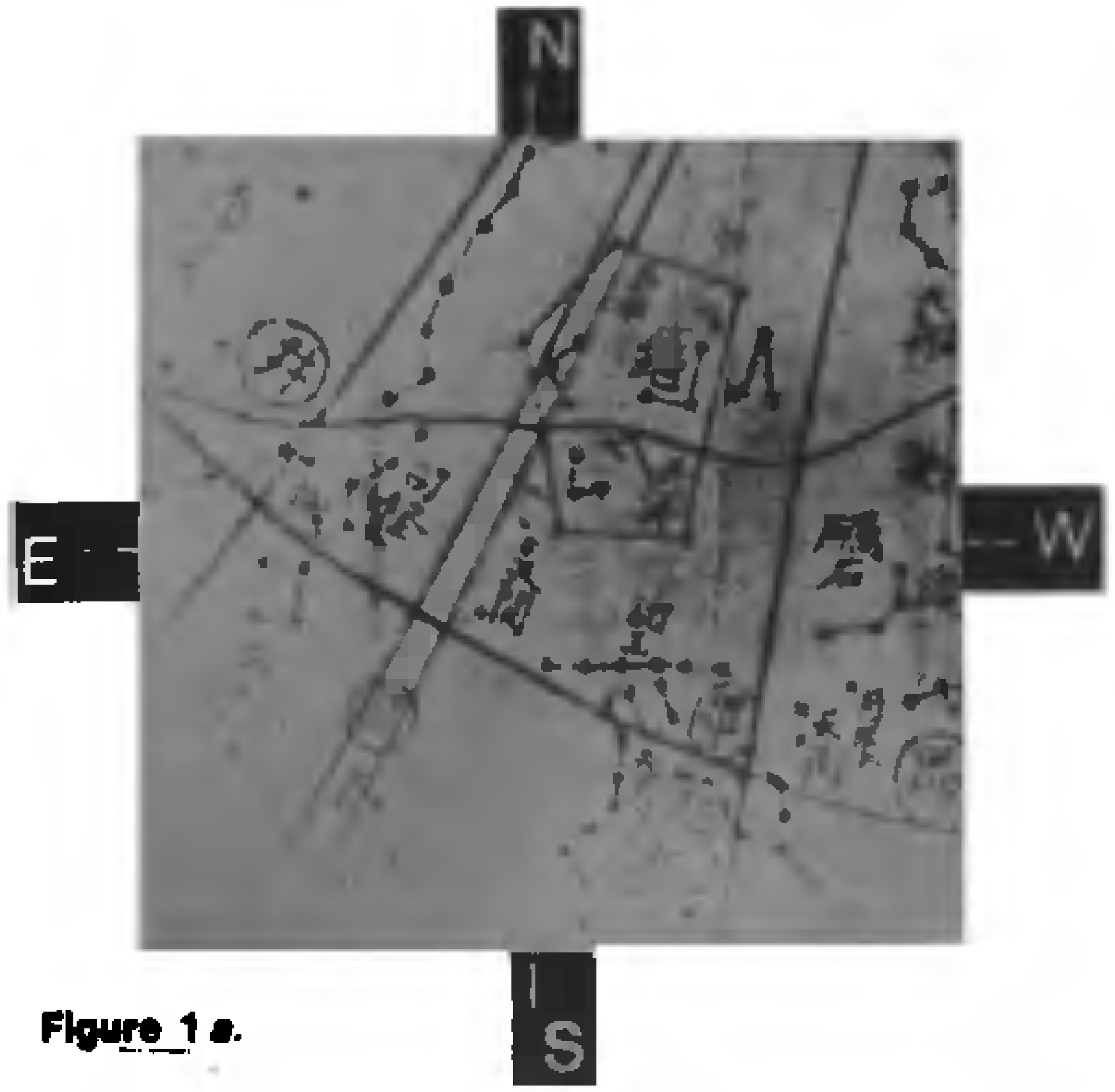

Figure 1 a.

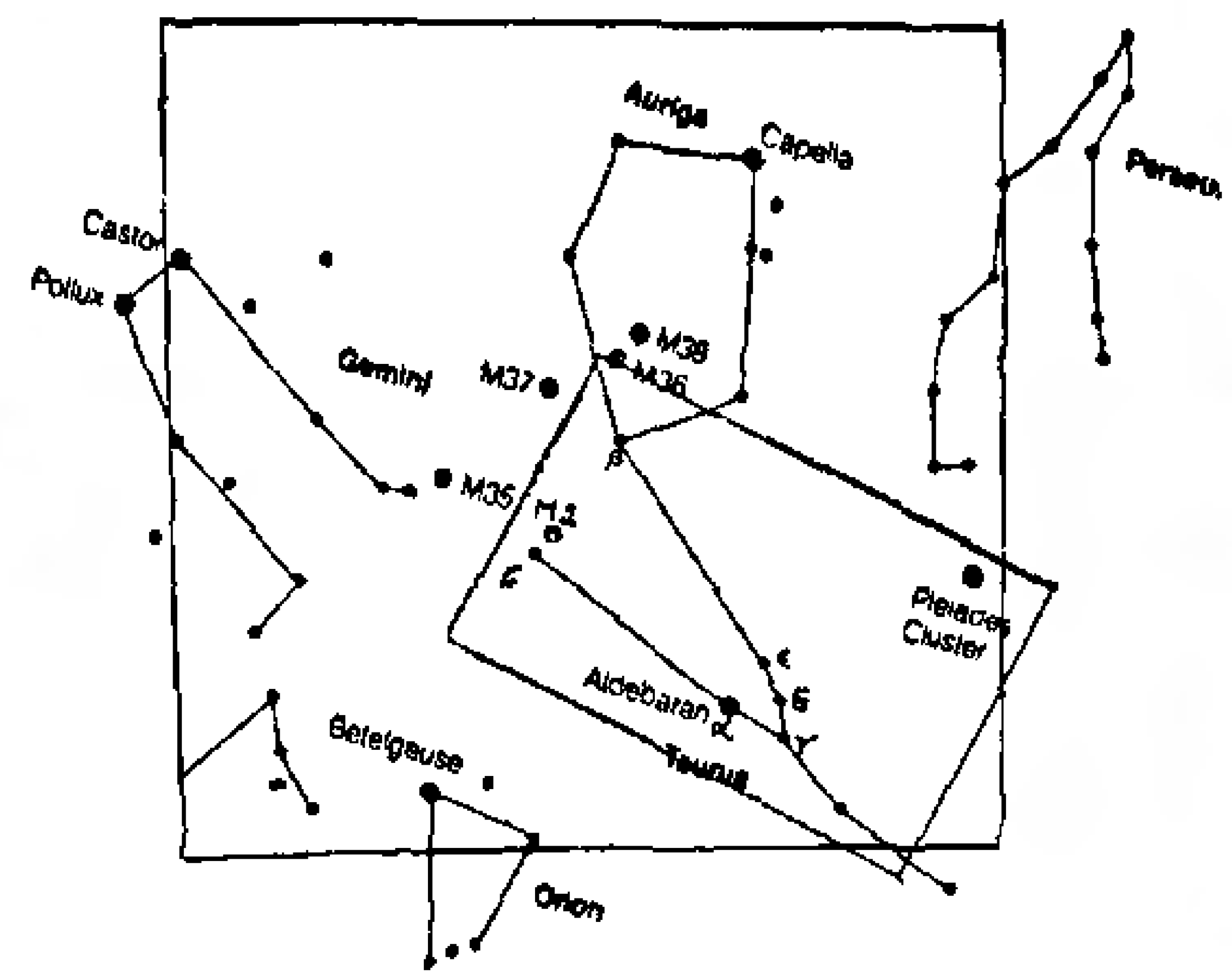

Figure 1 b.

Figure 2.

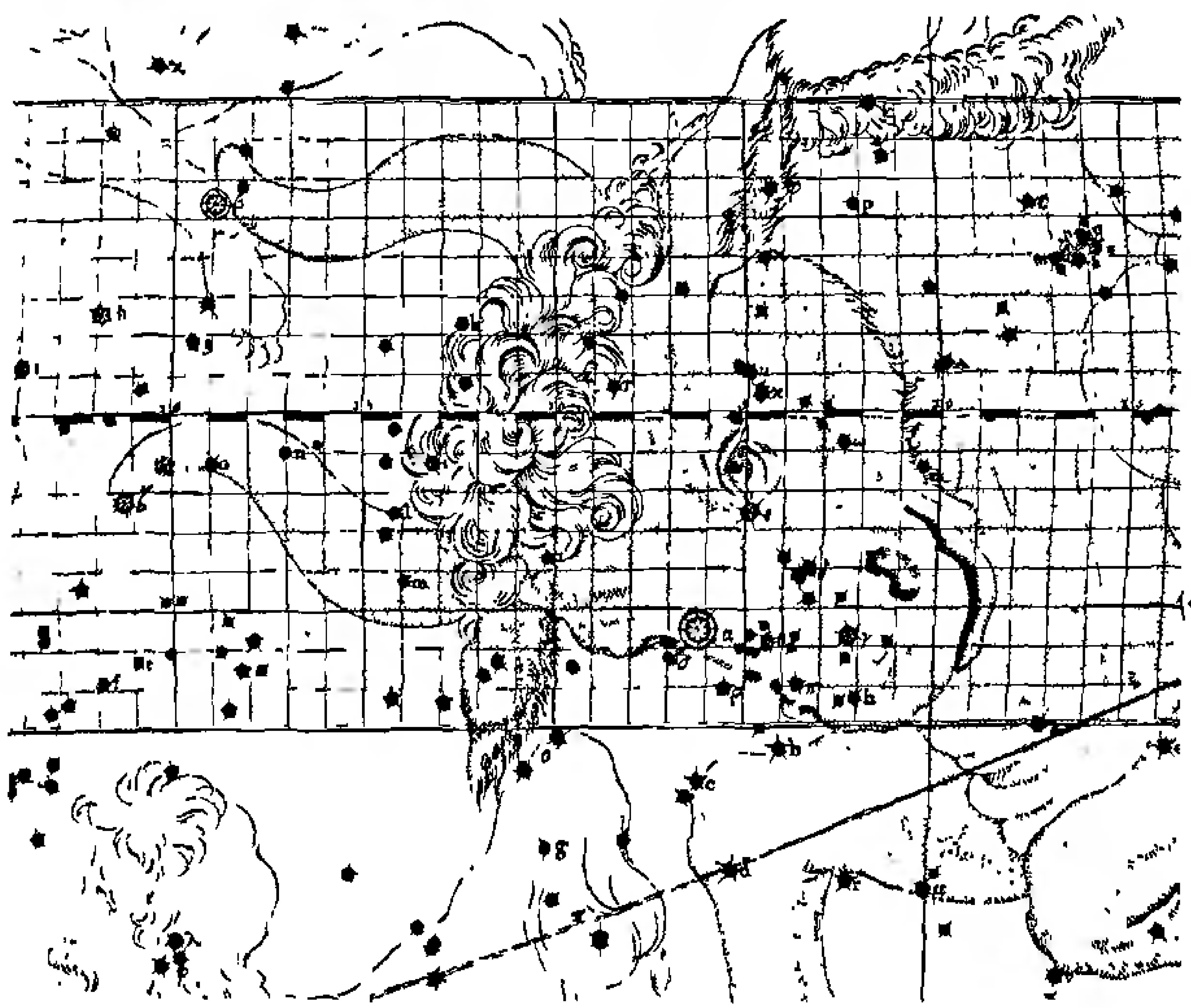

Figure 1 a. The rubbing taken from a Chinese stone chart (the rubbing is now at the National Academy of Sciences in Washington, DC) The guest star (the Crab Nebula, M1) which appeared on 4 July 1054 is just below and to the left of the large polygon of stars

Figure 1 b, *Line drawing of Figure 1 a Rectangles show the extent of the figure in 1 a* and 3

Figure 2. The pictograph on a sandstone surface at Chaco Canyon, New Mexico, USA, depicting the crescent moon and a star Astronomers and anthropologists feel that this star is a probable representation of supernova of 1054, made on 5 July 1054

Figure 3. John Bevis, a London physician, one of the active observers of the heavens, discovered the Crab Nebula about the year 1731 He compiled a set of ornate star charts A portion of the Plate XXIII from *Uranographia Britannica* showing the constellation Taurus The nebula is the faint round symbol above and to the right of Zeta Tauri The small rectangle, Figure 1 *b*, shows the region in the drawing Figure 3 Messier in 1758 discovered a nebulous object which he thought was Comet Halley He was wrong since the nebula in Taurus was first listed in Messier's Catalogue, and is known as M1 The third Earl of Rosse who built large telescopes for observing nebulae and star fields, published the drawing of the nebule and he used the term Crab Nebula owing to its superficial resemblance to a crab

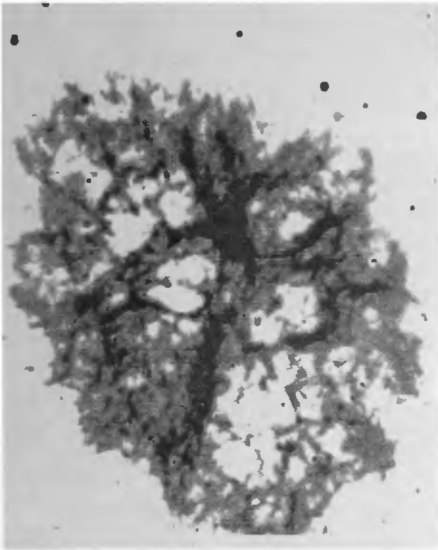

Figure 3. The filamentary shell of the Crab Nebula in the light of [O III] λ 5007 Å imaged with a CCD at the 1.2-m telescope at the Observatoire de Haute Provence by M. P. Veron-Cetty.

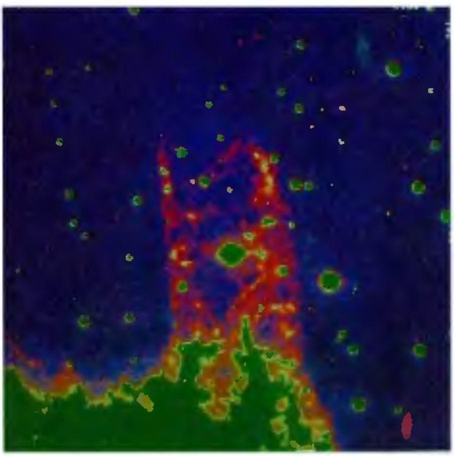

Figure 4. The 'Jet', in the light of [O III] λ 5007 Å imaged with a CCD at the 2.2-m telescope at the ESO La Silla Observatory by M. P. Veron-Cetty. Different colours correspond to different intensities.

cylinder of fine filaments with remarkably straight edges. The axis of the cylinder points towards the central area of the Nebula. However, a more precise analysis shows that it does not point to the pulsar, neither at its present location nor at its location in 1054. Inside the cylinder a faint synchrotron continuum has been detected at radio and at optical wavelengths with a spectrum not very different from that of the Nebula. The radio polarization indicates a magnetic field predominantly parallel to the axis of the cylinder. Explanations advanced for the origin of the Jet include an instability in the magnetic fields near the shell, shadowing by a dense interstellar cloud at the base of the Jet and a relic tunnel from the mass loss phase of the presupernova moving through the interstellar medium. None of the explanations is without problems.

The Crab Nebula and other supernova remnants

Some 200 supernova remnants (SNR) are known in our galaxy and in the Magellanic Clouds. They come in two principal varieties characterized by their images at radio wavelengths: shells and center-filled remnants. The shells are due to a (complex) shock propagating out into the interstellar or circumstellar medium, pushed by the ejecta of the supernova. In the shock relativistic electrons (and nuclei ?) are accelerated, magnetic fields are amplified by turbulent processes, and the resulting radio emission is observed. The radio spectra are relatively steep ($\alpha \approx 0.7$ rather than 0.3 as in the Crab Nebula) and consequently optical synchrotron radiation is not detectable. X-ray emission by hot plasma behind the shock and optical emission lines from cooler, denser filaments are frequently observed. The center-filled SNR are rarer; they look more like the Crab Nebula. Intermediate objects with a small center-filled core surrounded by a shell further out also occur. It is frequently believed that the center-filled SNR are pulsar-driven. Of six SNR formed within 10^4 light years from the sun during the last thousand years two are center-filled (Crab and 3C 58) and four are shells (SN 1006, Tycho's SN, Kepler's SN and Cas A) without a trace of a center-filled component[25]. Among more evolved SNR, the shells are more common, but this may be due in many cases to the Crab-like component having become extinct. Pulsars have been detected in only a few SNR. If pulsars emit strongly beamed radiation, this is perhaps not surprising. The absence of center-filled morphologies in the four recent SNR cannot be explained this way. It is possible that only a relatively small fraction of supernovae leave neutron stars. Perhaps more probable, neutron stars may be more frequent, but with too slow a rotation[26] or too weak a magnetic field to produce a detectable pulsar nebula.

With regard to chemical composition the Crab Nebula remains unique. In other young SNR evidence for enhanced abundance of elements like O, S, Ca, Ar, Fe and others has been found. No other case is known with a very high helium abundance without heavy element anomalies. Another peculiarity of the Crab Nebula is its low expansion velocity. The other nearby center-filled SNR 3C 58 probably expands at 2500 km s^{-1} (if the 2 kpc distance is correct), but the four recent shell sources expand with velocities ranging from 5000 to 7000 km s^{-1}.

Typical pulsars appear to be formed with substantial velocities. It is not entirely certain how these are caused. Perhaps the supernova explosion was asymmetrical; an asymmetrical energy output by a pulsar also may play a role, as maybe the orbital motion of a presupernova star in a binary. It is interesting to see that also the pulsar in the Crab Nebula has a motion of about 100 km s^{-1}. The motion is directed towards the NW, in the *same* direction as the one in which the strongest evidence for energy input into the Nebula is seen and therefore incompatible with some kind of rocket effect. The fact that the helium abundance is largest to the south could perhaps indicate the importance of an asymmetrical explosion, but a plausible scenario is still lacking.

Conclusion

The Crab Nebula has profoundly influenced the evolution of our thinking not only on supernovae but also on particle acceleration and magnetic field generation in Active Galactic Nuclei. It has been a prototype for a variety of astrophysical processes, but in many ways it seems to be a rather exceptional object.

We seem to understand the process of the acceleration of relativistic electrons and positrons in a general way, and the energetic balance seems about right. We still do not have a theory which explains the electron energy spectrum injected into the Nebula by the pulsar, and also the subsequent propagation of the electrons and the structure of the magnetic fields in which they move is only dimly understood.

The synthesis of a large amount of helium has been clearly documented, but the absence of any other evidence of nucleosynthesis remains somewhat puzzling.

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