PAPER 54

OPTICAL EMISSION FROM THE CRAB NEBULA IN THE CONTINUOUS SPECTRUM*

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Extensive progress of radio astronomical methods of investigation during recent years has totally changed our ideas about the nature of the enevelopes ejected during the outburst of super-novae and, consequently, also about the phenomenon of the outburst of the super-nova [1]. The only envelope of a super-nova, investigated in sufficient details by means of optical astronomy, is the Crab nebula (see W. Baade [2], Minkowski [3], Greenstein and Minkowski [4], Barbier [5]. All available explanations concerning the nature of the Crab nebula are based upon these investigations. They were also applied in general to envelopes of other super-novae. Considering the Crab nebula as a typical super-nova remnant let us shortly discuss these statements.

According to [2] the Crab nebula consists of two mutually penetrating parts: a system of comparatively thin filaments, located on the periphery of a nebula, expanding with the velocity of 1000–1300 km/sec and an amorphous mass filling the inner part of the nebula. The expanding 'network' of the filaments gives the line emission, the amorphous mass a strictly continuous emission spectrum. According to [3] the radiation from the Crab nebula in the emission lines constitutes only several per cent of the total

* The new interpretation of the emission from the Crab nebula generally accepted at present was published by me in 1953 (see [1]).

During Professor Oort's visit of the U.S.S.R. in the summer of 1954 in connexion with the opening of the restored Pulkovo Observatory, I informed him about this new interpretation and excited his most keen interest to this problem. Professor Oort together with Dr Walraven developed and extended our investigations (J. Oort and T. W. Walraven, *B.A.N.* **12**, no. 462, 285, 1956). In particular, the extremely interesting observational data obtained by the U.S.A. investigators was used by Professor Oort.

The new important results on the polarization of the Crab nebula obtained by the Dutch, American and Soviet astronomers were not taken into account in the present paper, since it was prepared earlier (in the spring of 1955—to be presented at the Dublin Assembly of the I.A.U., where it could not be published for some technical reasons).

Some new important results confirming our interpretation of the nature of the Crab nebula were obtained recently in the U.S.S.R.

luminosity of the amorphous mass in the continuous spectrum. From colour indices given in [3] (interstellar absorption taken into account) it follows that the intensity of the radiation in the continuous optical spectrum per unit interval of frequencies, decreases with the growth of frequency approximately as $\sim \nu^{-1}$.

All statements concerning the physical conditions in the Crab nebula were until recently based upon the interpretations of its continuous spectrum, Baade [2] and Minkowski [3] do not admit the possibility of some mechanism of radiation in the continuous spectrum, except the free-free and free-bound transitions in the strongly ionized gas matter of the nebula. This radiation is, according to [3] excited by the exclusively hot star, a former super-nova. Such a mechanism of radiation is natural at first sight. No processes of scattering could, naturally, explain the observed radiation of the Crab nebula, the magnitude of the nebula equalling 9^m, and the magnitude of the two stars in the centre of the nebula about 16^m. The radiation of that nebula might only be its proper radiation.

Other mechanisms in a diffuse medium creating a continuous spectrum were unknown.

Later on in order to explain the faint continuous spectrum of the planetary nebulae A. J. Kipper introduced successfully the mechanism of 'splitting of L alpha quanta' [6]. If, however, this mechanism should be responsible for the emission from the amorphous part of the Crab nebula intense H-lines should be produced, which is not confirmed by observations. The distribution of energy in the continuous spectrum would be different from what is observed as well. The modification of Kipper's mechanism—'splitting' of the quanta of the helium resonance line—cannot explain the continuous spectrum of the Crab nebula owing to the same cause.

Supposing, however, that the continuous spectrum of the Crab nebula is caused by free-free transitions we meet with extreme difficulties and contradictions. Many of these difficulties were known earlier, but no attempts were made to analyse them critically, because there were no doubts that the Baade-Minkowski's mechanism of continuous emission may be erroneous.

Let us shortly discuss these difficulties.

An inevitable consequence of the accepted mechanisms of emission is the conclusion that (*a*) the kinetic temperature of the Crab nebula is extremely high—of the order of hundreds of thousands degrees, or even higher (because the discontinuity of the Balmer series and He^+ is observed), (*b*) the concentration of electrons in the Crab nebula is of the order of $10^3\,cm^{-3}$, (*c*) the mass of the nebula is about $20 M_\odot$.

If one considers that the radiation emitted by the nebula is caused by the central hot star—a former super-nova—the temperature of the surface of that star must be excessively high, higher than 500,000°, its radius being extremely small, less than $0{\cdot}02 R_{\odot}$ [3]. Professor Oort, retaining the mechanism of emission from the amorphous mass of the Crab nebula, believes in consequence of the evidently fantastic characteristics of the hypothetical central star, that the hot amorphous mass is not excited at all [7]. According to Oort's opinion, the hot nebula has retained the temperature of the inner part of the almost totally exploded central star. He suggests that the process of cooling of such an extremely hot extended mass of gas is going on sufficiently slowly. It is, however, difficult to admit the hypothesis that during an outburst of a super-nova it is getting destroyed and scattered. Spectral and photometric observations of the outburst of super-novae in other galaxies and energetic considerations contradict this hypothesis.

Quite recently Ramsey advanced a hypothesis that the high temperature of the amorphous mass of the Crab nebula may be maintained by the processes of radio-active decay of some non-stable isotopes, formed in the process of the explosion of a super-nova [8]. However, as it may be shown, this hypothesis is beneath criticism.

Thus, the suggestion that the amorphous mass represents a totally exploded star and that no external agent (like the ultra-violet emission of the central star, for example) is required to maintain the extremely high kinetic temperature, is deprived of any serious reasons. There are still less reasons to believe that the central star—a former super-nova—possesses the same characteristics, which result from Baade and Minkowski's interpretation of the continuous spectrum of the Crab nebula.

The morphological peculiarities of the Crab nebula seem altogether incomprehensible if such interpretation is admitted. The kinetic temperature of the filaments is rather low—about 10,000°. Their density cannot, therefore, be very high. The most intense lines in the spectrum of the filaments are $\lambda 3727$ (O II) and $\lambda 6548$–6584 (N II). The transition probability is extremely small for such lines. They are, therefore, getting intensified in the case of nebulae with low densities. The concentration of the particles in the filaments hardly exceeds 300–400 cm^{-3}. The fact of a long-lasting co-existence of comparatively cold and sufficiently diffuse filaments and an extremely hot diffuse mass with a not lesser density seems improbable. How are these filaments moving through the amorphous mass for 900 years?

The low state of excitation and ionization is, further, also quite incomprehensible. The rapid and 'energetic' electrons must inevitably enter into the filaments from the amorphous mass and cause ionization of atoms. It is also unclear, why the powerful ultra-violet emission of the central star (or of the diffuse hot mass) does not cause strong ionization in the filaments.

Let us point out that we observe co-existence of an extremely hot coronal matter and comparatively cold protuberances. However, in this case the picture is altogether different: the density of the 'cold' protuberanes is 2–3 orders higher, than that of the 'hot' corona, while in the Crab nebula the density of the filaments and of the amorphous mass is similar.

Finally, it is unclear why the nebulae—remnants of super-novae outbursts of 1572 and 1604—are so weak as compared with the Crab nebula. If the outburst of a super-nova signifies a complete destruction and scattering of the star, why do we not observe, in the places where super-novae have flared up, bright nebulae with continuous spectrum, remnants of the outbursts of such super-novae?

We underline that all these difficulties are the consequence of the interpretation of the continuous spectrum of the Crab nebula according to Baade and Minkowski.

In so far as these difficulties are insurpassable, according to our opinion, some other explanation of the continuous spectrum of the Crab nebula should be searched for.

New and important facts, which may throw light upon the nature of the Crab nebulae were revealed after the earlier studies by Baade and Minkowski had been published. The discovery of the radio emission may be given as an example. The spectrum of that emission is much more slow than for other sources. In the enormous spectral interval from $\lambda = 750$ cm to $\lambda = 9{\cdot}4$ cm, embracing about seven octaves, the flux F_ν of radio emission decreases for only 2·5 times. The Soviet radio astronomers discovered recently the radio emission of the Crab nebula on the 3·2 cm wave. But the value of the flux in this wave-length is somewhat less than that on the 9·4 cm waves [9]. It may, thus, be stated, that in the interval of eight octaves the flux of radio emission from the Crab nebula decreases 3–3·5 times. The law of the variation of the flux with the growth of frequency in the range of decimetre and centimetre waves may be written as $F_\nu \sim \nu^{-0{\cdot}2}$.

It is evident that the radio emission of the Crab nebula cannot stop abruptly at $\lambda_1 = 3{\cdot}2$ cm, being zero for $\lambda < \lambda_1$. It is beyond doubt that the flux of radio emission exists also for $\lambda \ll \lambda_1$, but the modern radio astronomical technique does not make possible the discovery of such emission.

It is to be questioned quite naturally whether the optical emission of the

Crab nebula with continuous spectrum does not form a continuation of its radio emission. In other words, cannot the radio and the optical emission of that nebula be caused by the same, but undoubtedly non-thermal, mechanism? It was shown in [10] and [4] that the radio emission of the Crab nebula cannot be considered as the prolongation of its optical emission in the continuous spectrum, assuming that the latter is of thermal origin, caused by free-free transitions. The problem that is advanced now is altogether different: it is not the radio emission that should be explained by the optical thermal emission, but vice versa—the optical emission must necessarily be explained by the non-thermal radio emission [1]. Thus, the mechanism of the optical emission of the Crab nebula with continuous spectrum must, according to this conception, be an extraordinary one, altogether different as compared with all thermal mechanisms of emission, which were known in astrophysics.

As it was found in [10] the flux of emission in the continuous optical spectrum per unit interval of frequency is in the case of the Crab nebula a thousand times less than in the range of metre waves. If in the interval of eight octaves of the studied range of radio emission the flux decreases three times, then it seems quite natural that it may become decreased for 300 times more in the interval of fifteen octaves that remain up to the optical range ($\lambda \sim 8000$ Å). The dependence of the intensity of the frequency in this range of spectrum may be approximately represented as $F_\nu \propto \nu^{-0\cdot5}$, it is to be much more 'steep' than in the range of decimetre and centimetre waves. In the range of the optical frequencies the spectrum becomes still more steep, $F_\nu \propto \nu^{-1}$, which is seen from the colour temperature of the optical continuous spectrum of the Crab nebula.

The only acceptable mechanism of radio emission of the Crab nebula may be the 'synchrotron'-emission of the relativistic electrons in magnetic fields [10].

Let us show the main equations describing this process.

The energy emitted by a relativistic electron, moving in a magnetic field will equal:

$$P(\nu, E)\, d\nu = 16 . \frac{e^3 H}{mc^2} \bar{\bar{P}}\left(\frac{\nu}{\nu_m}\right) d\nu, \tag{1}$$

where E is the energy of the electron, H the component of the magnetic field, perpendicular to the direction of the velocity. The function $\bar{\bar{P}}(\nu/\nu_m)$ reaches maximum for $\nu/\nu_m = 1$. In this case $\bar{\bar{P}} = 0\cdot1$. Further,

$$\nu_m = \frac{eH}{2\pi mc} \cdot \left(\frac{E}{mc^2}\right)^2 . \tag{2}$$

Let the differential energetic spectrum of relativistic electrons be

$$N(E)\ dE = \frac{K}{E^{\gamma}}\ dE.$$

The intensity of emission is

$$I_{\nu} = \frac{1}{4\pi}\iint P(\nu, E)\ N(E)\ dE\,dR = (2\pi)^{\frac{1}{2}(1-\gamma)} . \frac{e^3 H}{mc^2}\left(\frac{2eH}{m^3 e^5}\right)^{\frac{1}{2}(\gamma-1)} . U(\gamma)\ K\ \nu^{\frac{1}{2}(1-\gamma)}$$

$$= 1{\cdot}6 \times 10^{-21} . (2{\cdot}8 \times 10^{8})^{\frac{1}{2}(\gamma-1)} . U(\gamma)\ K . H^{\frac{1}{2}(\gamma-1)} \lambda^{\frac{1}{2}(\gamma-1)}$$

$$\times R\ \mathrm{erg\,.\,cm^{-2}\,.\,cycles^{-1}\,.\,steradian^{-1}}.$$

where R is the length of the emitting region, $U(\gamma)$ for $\gamma = 1{\cdot}2$ and 3 equals 0·37, 0·125 and 0·087, respectively [11].

The flux of emission $F_{\nu} = \int I_{\nu}\, d\Omega = I_{\nu} . \bar{\Omega}$.

The solid angle of the Crab nebula is $\bar{\Omega} = 2 \times 10^{-6}$. The length of the nebula is $R \approx 1$ pc $= 3 \times 10^{18}$ cm.

It may be expected that in the Crab nebula $H \sim 10^{-3}$ gauss [12]. In the radio interval of the spectrum $F_{\nu} = 1{\cdot}8 \times 10^{-23}$ watts/m^2 and changes as $\lambda^{0{\cdot}2}$. Here $\gamma = 1{\cdot}5$ and according to [3] $K \sim 3 \times 10^{-8}$.

The concentration of relativistic electrons in the Crab nebula responsible for its radio emission will then be:

$$N = \int_{E_1}^{E_2} N(E)\ dE = K \int_{E_1}^{E_2} \frac{dE}{E^{\gamma}}.$$

For the metre waves of radio emission $E_1 \approx 3 \times 10^{7}$, $E_2 = 3 \times 10^{9}$ eV, from which $N \approx 10^{-5}$ cm^{-3}. The total energy of these electrons equals

$$E = V \int_{E_1}^{E_2} N(E)\ E . dE \approx 4 \times 10^{47}\ \text{ergs},$$

where the volume of the Crab nebula is $V \approx 10^{56}$ cm^3. The energy emitted by the super-nova during its outburst may reach 10^{49}–10^{50} ergs.

We shall assume that the optical emission with continuous spectrum is caused in the main by relativistic electrons [1]. However, if the electrons with energies 10^{7}–10^{9} eV are responsible for radio emission, the optical emission will be caused in the main by the electrons with energies about 5×10^{11}–10^{12} eV (in so far as $\nu_m \propto E^2$; see [2]). Let us, in the same way as above, estimate the concentration of such electrons.

For $\lambda = 5 \times 10^{-5}$ cm ($\nu = 6 \times 10^{14}$ sec^{-1}), $F_{\nu} = 1{\cdot}5 \times 10^{-23}$ ergs/cm^2/sec cycle/sec [10], the exponent of the energy spectrum of the quick electrons $\gamma = 3$, $U(\gamma) = 0{\cdot}087$. According to [8], $K = 3 \times 10^{-9}$ the concentration of electrons with energies $E > E_0 = 5 \times 10^{11}$ eV and

$$K . \int_{E_0}^{\infty} \frac{dE}{E^{\gamma}} = \frac{K}{2E_0^2} \approx 2 \times 10^{-9}\ \text{cm}^{-3}.$$

The energy density of the electrons with energies $E > E_0$ will equal

$$K\,.\,1/E_0 \approx 4\times 10^{-9}\,\text{ergs/cm}^3.$$

It will namely be of the same order as the energy density of softer relativistic electrons, responsible for its radio emission.

Thus, the altogether insignificant amount of relativistic electrons is the cause of a comparatively powerful optical emission. An extremely important conclusion may be made from it: the mass of the 'amorphous' part of the Crab nebula cannot be very great. If in the internal part of the nebula only relativistic particles would be present, its mass should be of the order of $10^{-6}M_{\odot}$.

It cannot be assumed that extremely interlaced magnetic fields can be present in vacuum. A sufficiently rarefied gas, which does not show itself optically, owing to its rarefication, must be present in the inner part of the nebula. The origin of this gas may, possibly, be the ejection of matter from the super-nova after the maximum. From an analysis of the diffusion velocity of relativistic particles in the Crab nebula and the dimensions of the turbulent elements contained in it it appears that $l = 3\times 10^{16}$ cm. However, it must be, at least, several times greater than the mean free path. An estimation of the lower limit boundary of the mass of the amorphous part of the Crab nebula may be established from it, which equals $M_1 = 10^{32}$ g. The real value of the mass of the amorphous part of the Crab nebula must be close to M_1. This follows from energetic considerations. The density of the kinetic energy must be close to the density of the magnetic energy $H^2/8\pi$. H cannot exceed appreciably 3×10^{-4} gauss. This means that $H^2/8\pi \leqslant 4\times 10^{-9}$ erg/cm³. Consequently, for $V \sim 3\times 10^{7}$ cm/sec the density $\rho \lesssim 10^{-24}$ g/cm³. It follows from it that the mass of the amorphous part of the Crab nebula is of the order of 10^{32} g, i.e. $0{\cdot}05_{\odot}$.

The mass of the filament system is also hardly exceeding several hundredths of the solar mass. This results from the estimation of the volume occupied by the filaments and from the density of the filaments $\rho < 7\times 10^{-22}$ g/cm³.

Thus, the mass of gases ejected during the outburst of the super-novae 1054 does not exceed, apparently, $0{\cdot}1\,M_{\odot}$, it is, namely, one hundred times less than the value assumed formerly.*

* Pikelner has recently explained that the well-known mysterious acceleration of the Crab nebula is caused by the pressure of the magnetic field in the nebula. Independent considerations permitted him to estimate the mean strength of the magnetic field of this nebula: $H \approx 3\times 10^{-4}$. Hence, owing to the acceleration of the system of filaments in the Crab nebula he determined its mass, established by him to be $0{\cdot}1\,M_{\odot}$, which coincides satisfactorily with our estimates (*A.J. U.S.S.R.* **33**, no. 6, 1956).

Such a comparatively small value of the mass of envelopes, ejected during the outbursts of super-novae, is of essential importance for the whole problem. It signifies that the outburst of the super-nova does by no means signify a disruption and scattering of stars. The process of an outburst of a super-nova does not differ much from the process of a nova outburst. The difference lies only in the scale of the phenomenon. There are of course qualitative differences between super-novae and novae outbursts, too. For instance, the brightest (according to their absolute magnitude in maximum) novae—are the rapid novae (see[13]), whereas in the light curves of the super-novae an enormous luminosity in maximum co-exist with a rather gradual decrease of light with time.

It may be understood now why no bright nebulae with continuous spectrum similar to that of the amorphous part of the Crab nebula are observed in the places of other galactic super-novae. It is certain that a sufficiently large number of relativistic electrons with $E > 5 \times 10^{11}$ eV is not originating in all outbursts of super-novae. Therefore, only a small number of radio nebulae should have a sufficiently strong optical spectrum. Special conditions are also required in order that relativistic electrons of high energies, originated at a definite stage of the development of a nebula, should not loose a considerable part of their energy during several centuries.

The apparent stellar magnitude of the systems of filaments of the Crab nebula will be about 12^m–13; only 3^m brighter than the magnitude of the nebula remnant of the nova 1604. This super-nova was 4^m fainter in maximum, than the super-nova of 1054.

If the optical emission of the Crab nebula with continuous spectrum is caused by relativistic electrons a polarization of this emission should be expected[14].

We paid attention to the fact that the expected polarization must have a small-cell character[13]. The light polarized in a given direction must arrive from a region, where the magnetic field is almost homogeneous. As we have seen above, the dimensions of such regions, $l \sim 3 \times 10^{16}$ cm, constitute approximately 1/50 of the dimension of the nebula, or 2–3″. An averaging of the polarization along the line of sight should take place, but statistically one must expect a 'non-compensated' polarization. The polarization can even reach 5–10 %.

The polarization of the Crab nebula, which has been predicted theoretically, was recently observed by Dombrovsky[15]. It was found that the polarization is of a rather regular nature. The main direction of the polarization is oriented along the axis of the Crab nebula. Such a character of the polarization may, possibly, be caused by the superposition of homogeneous interstellar magnetic field, which existed in the region of the space, where the super-novae of 1054 had burst. Thus, a randomly oriented magnetic field in the Crab nebula must have a component (equalling about 10 %) of a regular nature. The presence of such a component will not affect essentially the diffusion velocity of the relativistic particles, but will assist its 'spreading' in this direction. The elongated form of the amorphous mass of the Crab nebula, may, possibly, be explained by it. Let us mention in this connexion that G. A. Shajn paid attention to the existence of preferential direction in IC 443 and the Crab nebula—doubtless remnants of old outbursts of super-novae [16]. He connected this fact with the existence of a general interstellar field in the place where the super-nova had outbursted.

Further detailed study of the polarization of the optical continuous emission from the Crab nebula is needed.*

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* After this paper had been written (in the spring of 1955) important investigations of the Crab nebula have appeared. These are namely the following: G. A. Shajn, S. B. Pikelner, R. N. Ikhsanov, *A.J. U.S.S.R.* **32**, 395, 1953; E. K. Khatchikian, *C.R. Acad. Sci. Arménie*, **21**, 63, 1955; J. Oort and T. Walraven, *B.A.N.* **12**, no. 462, 285, 1956; W. Baade, *B.A.N.* **21**, no. 462, 312, 1956.