being investigated. There are indications that the radius of the cylinder on which lie the nine outer pairs of fibres is larger for the mutant than for the control, but more measurements are required to justify this observation on statistical grounds. There appear also to be differences in the proportions of the complex basal body structure; these too require further examination.

Summary

(1) A mutant non-motile or 'paralysed' strain of *Chlamydomonas reinhardii* has been produced in the presence of proflavine and isolated.

(2) Electron microscope examination of the flagella of the mutant shows an abnormal structure, the most obvious feature of which is the apparent lack of a central pair of fibres in an organized form.

(3) Tetrad analysis of crosses between mutant and wild type has demonstrated a 1 : 1 segregation on the basis of motility and also in terms of fine structure (as described in (2)) in the electron microscope.

(4) *Chlamydomonas reinhardii* appears to be a suitable organism for the investigation of the morphogenesis of flagella. The mutant pro_1 of *Chlamydomonas reinhardii* is believed to be one of the first to be isolated with a clearly observable alteration in the fine structure of a well-characterized organelle, the flagellum.

We thank P. J. Hastings of the Botany School, University of Cambridge, for initiating us into various techniques of handling *Chlamydomonas*, particularly tetrad analysis.

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ELECTROMAGNETIC WAVES FROM VERY DENSE STARS

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THE recent detection of X-rays from the region of the Crab Nebula and from a discrete source in Scorpius by Giacconi *et al.* and by Bower *et al.*[1–3] has much increased the interest in neutron stars (cf. Chiu[4] and Morton[5]). It has been considered important for the maximum mass of a stable neutron star to exceed that permitted for a white dwarf, about $1{\cdot}3\ M_\odot$. The original discussion of the problem by Oppenheimer and Volkoff[6], treating neutrons as a simple Fermi gas, gave a maximum mass of only $0{\cdot}7\ M_\odot$. However, allowance for a hard core nucleon potential increases the maximum mass and it is likely that in the stiffest possible situation with the pressure equal to the energy density the maximum mass for a neutron star does exceed that for a white dwarf[7]. This has been considered essential in order that neutron stars be formed during the course of stellar evolution.

We begin by pointing out that for actual stars possessing rotation the usual treatment of the maximum mass has no general validity. When gravity is balanced by centrifugal force in directions perpendicular to the axis of rotation there is no limit to the mass which may be supported in a disk-like structure. For a disk of radius a, thickness b, in which the material has angular momentum h per unit mass, we have the following relations:

$$h^2a^{-4} = \omega^2 \simeq 2\pi G\rho \qquad (1)$$

$$P \approx 2\pi Gb\rho.b\rho \qquad (2)$$

where P is the pressure. Equation (1) is necessary for the rotational support and equation (2) is necessary in order that the pressure shall balance gravity in the direction perpendicular to the disk. The mass M is given by:

$$M = \pi a^2.b\rho \simeq \tfrac{1}{2}h\sqrt{\frac{P}{G^3\rho}} \qquad (3)$$

in which a has been eliminated with the aid of equation (1) and b with the aid of equation (2). Whatever the dependence of the pressure on ρ, it is clear that M can be made as large as we please simply by increasing h. At constant ρ, b remains constant while a increases with h, so that b/a decreases with the increasing h and the disk-like property assumed here is enhanced as $h \to \infty$.

Our second point is that a neutron star is thought to be formed catastrophically, probably through the free fall collapse of a supernova. This means that such a star does not arrive gently at its stable configuration. Large dynamical velocities are developed and there must be oscillations about the stable configuration. For situations in which the dimensions of the equilibrium structure are not much greater than the critical Schwarzschild radius, the dynamical speeds are not much less than speed of light. Since for neutron stars the dimensions of the equilibrium structure are taken as not more than 3–10 times the Schwarzschild radius, the corresponding speeds are $\sim c/3$, and the associated dynamical energy is of order 10^{20} ergs gm^{-1}. Not until after this energy of oscillation has been dissipated can the stable structure be arrived at. The question we wish to raise is: How is the dynamical energy of oscillation, totalling $\sim 10^{54}$ ergs for a star of mass $5\ M_\odot$, dissipated? Our suggestion is through the emission of electromagnetic waves.

For definiteness we shall consider a neutron star with a mean internal density of order 10^{15} gm cm^{-3} and with dimensions $\sim 10^6$ cm. It seems unlikely that the magnetic intensity at the surface can be much less than 10^{10} gauss. Even a star with such a small dipole field as the Sun, 1 gauss at a mean density of ~ 2 gm cm^{-3}, would develop a polar field of $\sim 10^{10}$ gauss if it were catastrophically contracted to $\sim 10^{15}$ gm cm^{-3}. (The magnetic field would not be squeezed out of the star. Although neutrons dominate, electrons and protons are

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also present, the sum of the top of their Fermi distributions being equal to that of the neutrons. The electrons have high conductivity.)

Dynamical oscillations of the main body of a neutron star evidently imply an oscillation of the associated magnetic field. The oscillations will be of a hydromagnetic character so long as the hydromagnetic wave speed $H/\sqrt{4\pi\rho}$ is appreciably less than c, as it is in the interior of the star. But ρ falls steeply at the surface, the scale height being only a few centimetres. Evidently, for $\rho \simeq 1$ gm cm^{-3} we have $H/\sqrt{4\pi\rho} \sim c$ and the situation becomes electromagnetic rather than hydromagnetic, with the displacement current of crucial importance. Outside the immediate surface we expect electromagnetic waves to be generated, $\lambda/2\pi$ being of the order of the dimensions of the star. This follows because the frequency ν is $v/2\pi R$, where v is the dynamical speed of oscillation, $\sim 10^{10}$ cm sec^{-1}, and R is a characteristic dimension. Hence, $2\pi\nu \simeq 10^4$ c/s, and $\lambda/2\pi \simeq 3 \times 10^6$ cm. The simplest example is that in which an oscillating star with an initial non-uniformity of rotation produces oscillating variations in the winding of a toroidal magnetic field, requiring an oscillating component in the axial current, that is, a Hertzian oscillator. The emission of electromagnetic waves serves in this case to damp the initial non-uniformity of rotation. On the other hand, an oscillating component in the toroidal current would seem to be necessary in order to damp out the radial oscillations of the star.

The possible rate of emission of energy by electromagnetic waves is very large. The Poynting vector $c\mathbf{E} \times \mathbf{H}/4\pi$ has magnitude $cH^2/4\pi$, which gives $\sim 3 \times 10^{29}$ ergs cm^{-2} sec^{-1} for $H = 10^{10}$ gauss. The total surface area is $\sim 10^{13}$ cm^2, so that the total emission rate might be as high as 3×10^{42} ergs sec^{-1}, although a lower value, say 10^{41} ergs sec^{-1}, would be a more conservative estimate, since the oscillating component of the field is likely to be less than the total field. However, even 10^{41} ergs sec^{-1} is sufficient to dissipate the available store of $\sim 10^{54}$ ergs in $\sim 10^{13}$ sec $= 3 \times 10^5$ years.

It is important that no propagation difficulty arises. Electromagnetic waves are damped out in a few wave-lengths when the dielectric constant:

$$1 - \frac{Ne^2}{\pi m \nu^2} \qquad (4)$$

becomes negative. Here N is the electron density and e,m are the electron charge and mass. Putting $2\pi\nu = 10^4$ c/s, it is easily seen that (4) is zero for $N \simeq 3 \times 10^{-2}$ electrons cm^{-3}. While this is only very small compared with the internal density of a neutron star, it is much greater than the likely exterior density at a few radii out from the surface, simply because the radius exceeds the scale height by a large factor $\sim 10^6$. The point is that the strong gravitational field of the star creates a near-vacuum immediately outside itself, and the electromagnetic waves are free to travel out into space. Moreover, any residual gas outside the star would simply be swept away by the pressure of the electromagnetic waves.

How does the electromagnetic flux from an oscillating neutron star lead to observable effects? So long as the dielectric constant (4) is positive the waves pass essentially freely through space, but a critical condition arises if (4) becomes negative, that is, if N exceeds $\sim 3 \times 10^{-2}$ electrons cm^{-3}. The waves will be reflected from any cloud they encounter in which this condition is satisfied, and the cloud is then subjected to radiation pressure. The consequent compression increases N so that the pressure, once started, continues. Although radiation pressure is usually thought of as a weak effect—this is true for optical radiation—the electromagnetic flux from a neutron star can be so large that dramatic possibilities arise.

Consider the case of the Crab Nebula. The total mass of the gaseous filaments is about 0·1 $M_\odot$, which is about the mass of interstellar gas to be expected in a volume of 1 pc^3, the volume of the Crab. The filaments are in outward motion with speed $\sim 1{,}000$ km sec^{-1}, so that the total outward momentum of the gas is $\sim 2 \times 10^{40}$ gm cm sec^{-1}. If this momentum has been derived from radiation, the energy of the radiation must have been 2×10^{40} c. Taken over 1,000 years the necessary mean energy output is $\sim 2 \times 10^{40}$ ergs sec^{-1}, close to the value 10^{41} ergs sec^{-1} estimated here. Hence it is possible that the observed outward momentum of the Crab has been derived from the electromagnetic flux.

Using 10^{41} ergs sec^{-1} for the total flux, the flux per unit area at $\sim 10^{17}$ cm from the emitting star is $\sim 10^6$ ergs cm^{-2} sec^{-1}. Reflected normally from a surface this flux exerts a pressure of $\sim 10^{-4}$ dyne cm^{-2}. Since reflexion occurs in only a few wave-lengths, in $\sim 10^8$ cm, the reflecting zone can indeed be thought of as a very thin layer in which the internal pressure must build up to match that due to the reflexion, $\sim 10^{-4}$ dyne cm^{-2}. If the electron density is 3×10^{-2} cm^{-3}, a mean electron energy of 10^{-2} erg $\simeq 10$ BeV is necessary to supply this pressure. Although this estimate would not be correct if the electron density were to increase to much more than 3×10^{-2} cm^{-3} in a distance of $\sim 10^8$ cm, it is clear that any steep increase of density must imply violent non-uniformity in the thin-surface zone, and that particle acceleration could well take place in the ensuing fine scale motions. The critical behaviour of the refractive index would therefore appear to provide a mechanism for the generation of the high-energy electrons necessary to explain the synchrotron emission of the Crab. If the electrons were derived from the star itself it would be hard to understand why their energies were not immediately degraded through synchrotron emission in the very high magnetic fields close in by the star.

Turn back to the formation by collapse of a neutron star: why should this phenomenon show up as a supernova? Hoyle and Fowler[8] considered that, while the inner regions of a supernova collapse, the outer regions are thrown explosively off into space through a rapid release of nuclear energy, but these considerations apply only to supernovæ of Type II. For Type I supernovæ there may well be no explosive emission of an outer shell. There is the possibility that the optical radiation of Type I supernovæ comes from circumstellar clouds, distant perhaps as far as 10^{16} cm, that are activated by the ensuing electromagnetic flux.

We end by enquiring whether a similar process might occur on a still larger scale. Ginzburg[9] has considered the problem of the magnetic fields associated with massive objects, 10^6–10^8 $M_\odot$. The problem appears essentially different, however, so long as one is dealing with a single coherent object. The wave-length would in any case be much larger, $\sim 10^{13}$ cm, and there would be a propagation difficulty similar to that aforementioned for ordinary stars. On the other hand, there is the possibility[10] that rotation may cause a massive object to break up into a swarm of neutron stars and/or white dwarfs. In such a situation each neutron star would behave essentially independently of the others, and with $\sim 10^7$ such stars the intensity of the phenomenon would be multiplied by this factor. The total energy available for electromagnetic radiation would then be $\sim 10^{61}$ ergs. A process of high efficiency, converting this energy into cosmic-ray electrons, would be necessary if the strong radio sources were to be explicable in these terms.

It is of considerable interest that the momentum associated with this total energy efflux is $\sim 3 \times 10^{50}$ gm cm sec^{-1}, which is sufficient to endow 10^{43}gm (5×10^9 $M_\odot$) with a recoil speed of 300 km sec^{-1}. The possibility must therefore be considered that a marked disturbance in the whole of the interstellar gas within a galaxy could be produced. Indeed, the possibility must not be excluded that the interstellar gas might be entirely expelled from a galaxy, or—if the gas were a sufficiently large fraction

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of the total mass—that a whole galaxy might be disrupted and scattered.

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OBITUARIES

Prof. James Franck, For.Mem.R.S.

Prof. James Franck died on May 21 at the age of eighty-one years. Born in Hamburg on August 26, 1882, Franck went to school there with indifferent success—as he was fond of relating—because he had trouble with classic languages. He began to study chemistry and geology in Heidelberg, but soon turned to physics and moved to Berlin where he graduated as Dr.Phil. in 1906, with a paper on ion mobility in gases. In 1907 he became research assistant to Prof. H. Rubens, in whose colloquia I first met him in 1908. I had the great good fortune to win his friendship and that of his family and to retain it for nearly sixty years. Only recently I was able to spend some weeks with Franck, visiting old friends together all over Europe, until a few days before his sudden death in Göttingen, on May 21.

In the First World War Franck went out as a private, was wounded, decorated and returned as a lieutenant. He was then assigned to a group led by the chemist F. Haber, who later, in 1918, made him a division head at the Kaiser-Wilhelm Institute for Physical Chemistry in Berlin-Dahlem.

How well I remember his famous lecture on May 22, 1914, "On the Excitation of the Mercury Resonance Line 2536 Å by Electron Impact" in which he reported his joint work with Gustav Hertz, which gave strong support to Bohr's new theory of the atom. Einstein said to me: "It's so lovely, it makes you cry!" Many a discussion between Franck and Otto Stern about those experiments I have listened to during the War years, whenever Franck happened to be in Berlin.

In 1920 Franck was called to a chair in Göttingen. Haber's farewell speech—at a party which Otto Hahn and I arranged—ended with the words: "There are three stages in the life of a scientist: becoming, being and representing; may representing come easy to you". I think Franck did not enter that last stage until a few months before his death, and it was not easy for him, despite the many honours that have come his way, among them the Nobel Prize in Physics in 1926 jointly with Hertz, the Max Planck Medal in 1953, the Rumford Medal in 1955, membership in many learned societies, and the election, in March 1964, as Foreign Member of the Royal Society.

Göttingen saw Franck's happiest and most fruitful period; he remained attached to it, received its honorary citizenship in 1953, and it is an odd turn of fate that he died there. There he did all his work on the transfer of energy in molecular collisions, as in the processes called quenching and sensitized fluorescence. Franck discovered the method of determining the heat of dissociation of diatomic molecules from band spectra by extrapolating the vibrational levels. His discussion of the coupling between electron transitions and vibrational motion led him to formulate the principle which was later put in wave-mechanical form by Condon and is known as the Franck–Condon principle. Thus the intensity distribution in band spectra and the existence of continuous molecular spectra came to be understood. The influence of those ideas has been far-reaching, particularly in photochemistry. His many pupils, still attached to Franck in affection and devotion, include such famous names as Blackett, Condon, Kopfermann, Kroebel, Maier-Leibnitz, Oppenheimer and Rabinowitch, to mention some of them.

Those happy days ended when Hitler came to power. When the racial laws were announced, Franck published a courageous open letter in which he resigned his chair. In view of his distinguished war service he might have been allowed to stay, but he did not wish to serve under a Government which treated his fellow Jews as outcasts. After an interlude at Copenhagen, with Niels Bohr, he went to the United States, first to the Johns Hopkins University and then to the University of Chicago, as professor of chemistry. Here his efforts were devoted to the elucidation of the most important of all photochemical reactions, the photosynthesis performed by green plants. It is a borderline problem between physics, chemistry and biology, and one of appalling complexity. Franck's last paper on that subject, in collaboration with J. L. Rosenberg, went to press only a few weeks before he died.

During the War he interrupted his own work for two years to direct the Chemistry Division of the Metallurgical Laboratory of the University of Chicago, a part of the Manhattan Project. He saw it as his duty to help develop a nuclear weapon as long as Hitler might be doing the same. But he felt strongly that the United States should not be first in using it, and other scientists felt similarly. Two months before Hiroshima, a joint letter which became known as the "Franck Report" was sent to the U.S. Secretary of War, Henry L. Stimson, presenting strong and wise arguments against the unannounced use of that dreadful new weapon and suggesting that its power be demonstrated by publicly exploding it over an uninhabited area. Perhaps the nuclear arms race could have been avoided if that letter had been heeded.

Franck enjoyed talking about his problems, not so much to explain them to others as to clarify his own mind. Once a problem had aroused his interest he was completely captivated, indeed obsessed by it. Common sense and straight logic were his main tools, together with simple, mostly home-made apparatus. His research followed an almost straight line, from his early studies of ion mobilities to his last work on photosynthesis; it was always the energy exchange between atoms or molecules that fascinated him.

Franck was equally interested in people. His kindness and generosity, not only to his friends and family but to everybody who needed help, were known to all who knew him. He was the most lovable of men because he loved people; kindness shone from his eyes. There must be many beside myself who now feel they have lost one of their best friends.

I wish to thank O. R. Frisch and H. G. Kuhn for valuable help in writing this notice. Lise Meitner

Prof. Isadore Fankuchen

The death of Prof. I. Fankuchen on June 27 at the age of fifty-nine leaves a great gap among crystallographers in the United States and particularly, also, in Britain. He was a figure very well known and loved in both countries.

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