# SESSION 8

# RADIATION MECHANISMS OF THE PULSAR

# 8.1 THE RADIATION MECHANISM IN PULSARS

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**Abstract.** The properties of the radio pulses from pulsars are described. The formation of pulses seems to be a geometric phenomenon, for which the beaming due to relativistic motion of the source is the only candidate at present. Values of the volume emissivity and surface flux density indicate that all the particles near the source must have relativistic energies.

It will be interesting, I think, to recall that in 1955 when we had a conference here there was a paper by Oort and Walraven which was on the polarization and radio emission mechanism of the Crab Nebula. At that conference we did perhaps begin to understand what was going on in the nebula, but also at that Conference there were papers by Shklovsky on the radiation from extragalactic objects, from the Galaxy and other objects, and, speaking for myself, I really did not understand these papers which nevertheless contained the key to the radiation mechanism from the discrete sources – the synchrotron radiation. I was hoping that Ginzburg would be here and would give a talk, which even if I did not understand it would give me the key to the radiation from the pulsars, but we have to manage without. I think that he might have helped because I think that the kind of plasma wave mechanism which he and Zheleznyakov and others have been discussing is perhaps the way into the problem. However, instead of discussing the theory I am going to substitute for Ginzburg's talk by giving the best summary I can manage of what I think are the important observations.

The most important thing about the pulsars is that they are periodic and that there is attached firmly to the rotating object a location containing the source. This location is defined by the integrated pulse profile. In Figure 1 are examples of the various well known profile shapes you can get by adding many pulses from a single pulsar. Now the shape of the profile I am going to call 'the window', and I will say that each pulsar has a fixed window through which it radiates, like a lighthouse has a rotating turret with a hole cut in which a lens is placed. The angular width of this window is not obviously dependent on period; it remains in the range of about 1–4% of the period, so that 1–4% of $2\pi$ gives the angular width. The pulse shape and width are independent of frequency to a first order. We know, of course, that for 1133 separation of the peaks does depend on frequency and we know that details in the shape of others, such as 2045, or one of those with multiple pulses, certainly do change somewhat with frequency but the phenomenon is basically broadband and well represented in the shapes of Figure 1. Next I want to emphasise, and indeed the demonstration yesterday of live pulses from 0329 emphasised it to you, that this is not the typical shape of an individual pulse. For some pulsars the individual pulses appear as discrete individuals with a typical shape and they also have a typical polarization pattern inside them. It looks very much as if the more complicated pulses which you sometimes see are made up of a series of different individual pulses.

*Davies and Smith (eds.), The Crab Nebula,* 431–440. *All Rights Reserved.*

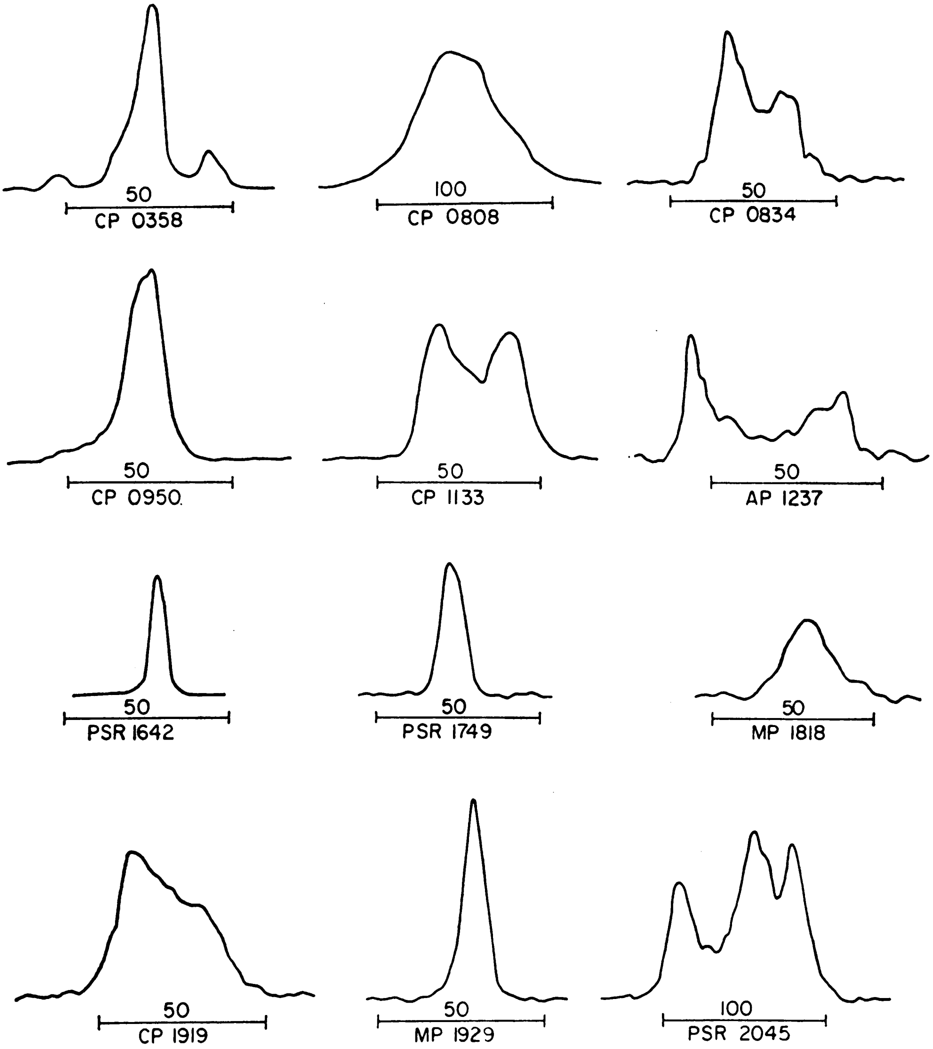

Fig. 1. Integrated pulse profiles at 408 MHz.

Wherever a single pulse appears in the window, it tends to have the same width. If you have a double profile I believe it is made up of two general locations inside which the pulses are liable to crop up. I believe that we must explain two things, the window and the individuals.

And if you are talking about a radiation beamwidth it should be the beamwidth derived from the width of the individuals, while the locations on the rotating object are determined by the window. It is as though you have a lighthouse with a turret in which the lens is rather poorly mounted so that it can shake about. If you want to describe the lens you think of what happens when a single beam goes past you.

If you want to describe the turret you add lots of appearances of the beam which tells you within what range the lens must be seated. So there are two angular widths to talk about.

The lens analogy is not bad because you can imagine the lens moving about rather slowly in its turret, corresponding to what we call pulse drift. A recognisable pulse appears on separate rotations and drifts across the window. They drift at definite rates in a given pulsar and a pulsar may have more than one rate. Not all pulsars show this clearly, but it could be that every pulsar has a rate and you do not easily see it because the pulses tend to die during one rotation, or move across so fast that they do not reappear. The source has a definite location within the window and it usually moves in a forward direction.

Now, of course, I have spoken about pulsars in general and I ought to interpolate the question: is the Crab pulsar the same? It is very difficult to say because we are unable to observe the individual pulses in such detail on many of these pulsars. For the Crab we are able, fortunately, to look at a few individuals because it has this peculiarity that it produces occasionally very strong individual pulses, and we believe that these individual pulses are very similar to those seen in other pulsars. We do not know really how to interpret the relationship between optical and radio pulses in the Crab Nebula. At first sight the envelopes, the integrated profiles, are very similar. It is surprising that you have got two sharp peaks of, say, a millisecond wide separated by 13 msec, and this happens equally at both ends of the spectrum. There are differences. I put it to you that those differences may be no greater than the differences which you find across the radio spectrum in any of the other pulsars. So let us say it is a very rough approximation that the integrated pulse shapes are much the same over the whole of the spectrum in the Crab. Obviously that needs a bit more argument and the sort of way to tackle it is to see whether the details of the individuals are the same as the envelope in the optical range as well as the radio range. That is where I found it very interesting to hear the results from Hegyi, who showed in fact that the optical pulses do follow all the same pattern and it is the sum of many similar identical pulses which is producing that profile. That may be a difference between the optical and radio behaviours.

Whether there is circular polarization in the individual pulses from the Crab is not yet proven, but there are after all other pulsars which do not produce much circular so that I do not think we can say whether that proves whether the Crab is the same or different from other pulsars. The individual strong pulses from the Crab, like those of other pulsars, behave in much the same way over a wide range of radio frequencies. If you get a strong pulse arriving early in the window of one frequency, then you get a strong pulse arriving early on all radio frequencies. Again this is a sweeping statement and we have not a lot of evidence. The evidence which we heard about differences between 111 and 74 MHz could be interpreted as saying that at least half the pulses do behave that way; for the other half we have to be careful about scintillation and so forth, and I feel they are perhaps really broadband also. So let us say that individual pulses are producing the same sort of intensity over a very wide frequency range.

How wide? It may be that the spectrum is not quite as wide as we think of when we can actually see pulses over several octaves. It could be that the typical width of a pulse, at half power points, is only an octave or so. There is some evidence that some of the pulsars are producing radiation which decreases towards the lower frequencies. For example, I think 0329 which you saw on the oscilloscope does peak somewhere about 400 MHz, which is fortunate because otherwise we would not have been able to demonstrate it.

The state of polarization is extremely important. It is elliptical in general, and you saw that it changes through an individual pulse. When it changes through an individual it changes only slightly by reversing hand once, or by a swing of position angle less than one radian. Examples can be seen in Figure 2. There is usually as much circular as linear in a typical pulse. When you add many pulses, the reversal of hand, which is variable, means that you lose the circular in most pulsars, and this has perhaps led many people to neglect this most important circular polarization in their theories. I would emphasise again that individual pulses are typically elliptically polarized.

The first thought about explaining this is that it might be synchrotron radiation from a beam of electrons being bent round a magnetic field and radiating in the forward direction. If you make the whole system rotate, the observer cuts across a fan beam. You see circular, linear, then circular. The degree of circular is very high, especially at the edge. This explanation looks right at first but what is wrong with it is the next observational fact, that the polarization is independent of frequency for both the integrated pulses and the position angles you get out of them. It also refers to individual pulses as Graham showed yesterday. If you photograph a single pulse, and manage to catch it at two frequencies which requires a little bit of slight of hand, you find that it has got the same pattern of polarization in it. So it is a very broadband phenomenon – you are not going to get away with it with a highly tuned maser or any other narrow band mechanism.

The next thing that we should say is that if it is synchrotron radiation, the width of the pulse should depend on frequency; and it does not. It should depend on frequency as $\nu^{-1/3}$, in the simple illustration I gave you, or if you take a spectrum of electrons in the usual way you can make it into $\nu^{-1/2}$, but you cannot make it stay still except by using a long tail of the synchrotron radiation way above the critical frequency when you must ask whatever has happened to all the radiation at the lower frequencies. So I think that this is impossible. You could therefore say that the width of the beam is not made by the $1/\gamma$ natural width of a beam of electrons but is made by a range of velocity vectors of the electrons spread over a range of angles which determines your beamwidth. This sort of theory is, indeed, a very attractive one because you can imagine your bunch of field lines and electrons going out, and Komesaroff has shown you can get nice beamshapes and nice polarization swings as in Radhakrishnan's theory. Others have taken up this idea as well. You can get a very nice arrangement of beamwidths but if you do that you lose your circular polarization because you are convolving the odd angular function with the wider angular beam. So you can produce the correct Stokes $I$, but not the correct Stokes $V$. If you have got circular

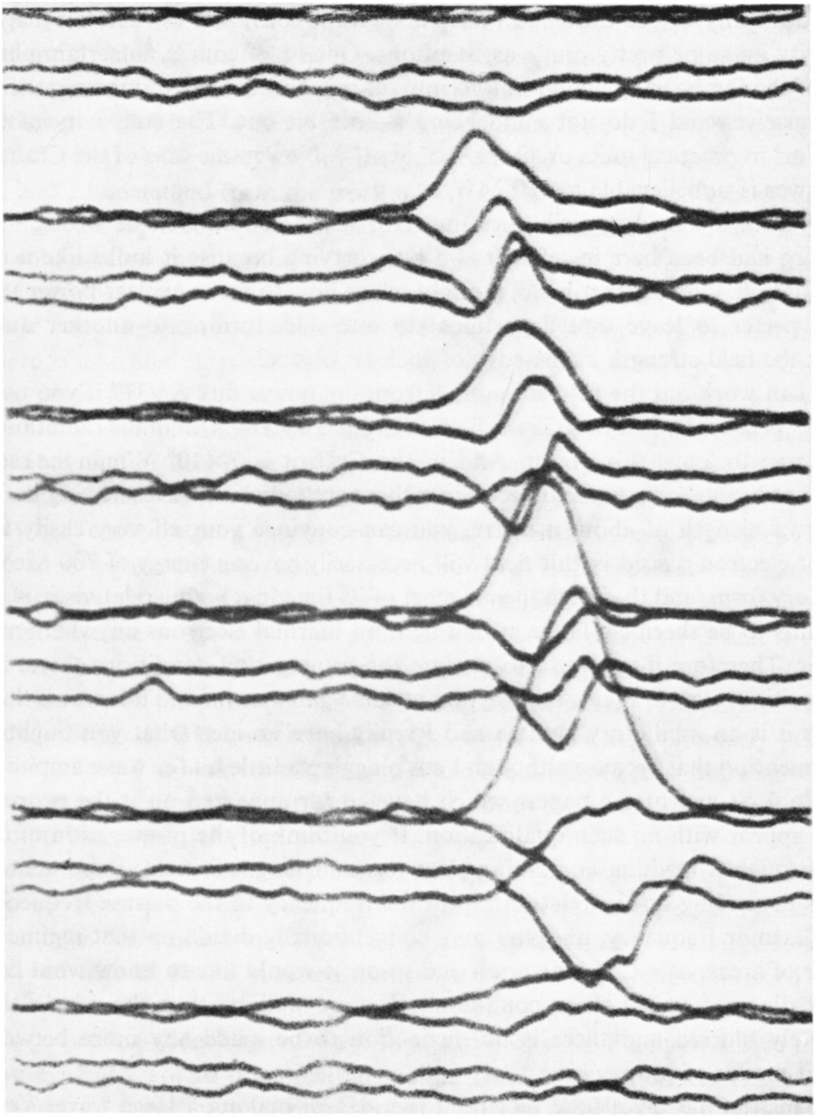

Fig. 2. A sequence of individual pulses from P 0329, recorded with a polarimeter at 408 MHz. The four traces record the Stokes parameters *I*, *V*, *Q* and *U* for each pulse.

you cannot have a beam which does not change its frequency on a simple synchrotron theory alone – that is out of the question.

I turn now to brightness temperature and intensity. You have already heard that the brightness temperatures exceeds $10^{28}$ K. The total intensity and volume emissivity are even more remarkable. Let us estimate the size of the source. It is fair to say that this looks like an object which is within the velocity of light circle of the pulsar, so I have just guessed that it might be 0.1 $R$ across where the radius $R$ is equal to $c\omega^{-1}$.

I have done this for the Crab and I have done it for 0329, and worked out the volume emissivity on some pretty crude assumptions. One is, of course, uncertain about the effect of the fan beam. I would not go into all this because the numbers rather speak for themselves and I do not mind being a little bit out. The emissivity of 0329 is 400 W/m$^3$ in practical units or 40 erg/sec$^{-1}$ cm$^{-3}$. Now in the case of the Crab pulsar, the answer is unbelievable at 100 MW/m$^3$.

Now there are many possibilities for error here. I could well be wrong – I wish Ginzburg had been here instead. It is a bit worrying because it looks like a nuclear power station. On the other hand, it might tell us how to make nuclear power stations. Now I prefer to leave that department to one side, turning to another question: what is the field strength at the edge of such an object?

You can work out the field strength $E$ from the power flux $E^2/377$ if you use these nice easy practical units. In 0329 the field strength is $5 \times 10^6$ V/m in the radiation which we observe to leave this object. And in the Crab it is $7 \times 10^8$ V/m in the radiation which we observe to leave the object. Since there are radiation waves leaving the source with a wavelength of about a metre, you can convince yourself very easily that an ambient electron placed in this field will necessarily have an energy of 700 MeV in an oscillatory form, and therefore spends most of its time in a highly relativistic way even if it wants to be thermal. There are, in fact, no thermal electrons anywhere near the radiator. Therefore if you wish to analyse the propagation conditions there, it is no use in writing $\omega/\omega_P$ or $\omega/\omega_L$, unless you put some gammas in, and it is worse than that because it is an oscillatory gamma and I really have no idea what you ought to do. Now I mention that because although I am plugging a little bit for wave amplification, if you look at any of the papers which have so far appeared on it the propagation factors appear with no such qualification. If you think of the propagation of a radio wave through a medium containing electrons and magnetic field, there are various regimes depending on the relationship of the frequency to the plasma frequency and to the Larmor frequency, and you may conventionally divide up that regime into a number of areas, as a CMA diagram and so on. I would like to know what happens to that diagram under these conditions. It may well be that the whole thing is completely blurred and there is no distinction to be made any more between the different modes of propagation.

Now just let me say a little bit about the idea of making a large wave. You may say in fact that if you have got to make a great big wave you could say 'some waves are born great, some achieve greatness and others have greatness thrust upon them'. 'Born great', by that I would mean you have got synchrotron radiation with bunches in it, and I do not think you ought to work that way because of this polarization and beamwidth problem. 'Some achieve greatness', well I think that is something like a maser; you have got to be careful with the maser because you have to get an adequate bandwidth. Now we heard that such things might be possible from Dr. Chiu; I would only worry a little bit that his radiation mechanism is near the surface and he has therefore got to produce a beamwidth with some configuration of field lines and I just do not know how he is going to do that and still produce the right circular and elliptical polarization. But it may be there is a broadband maser. 'Greatness thrust upon them', I think that would be a reasonable description of the enormous plasma waves that must be present, and the enormous plasma waves coupling with electromagnetic waves may indeed thrust greatness upon them. So we ought to look carefully first of all whether the energy from the pulsar can be converted easily into plasma waves, and I understand from the work of Tsytovich, Kaplan, and others that there will be indeed a rapid conversion of the energy of any relativistic particles into plasma waves, so doubtless they can exist. There is also the possibility that those waves will become rapidly isotropic and I do not know what happens to their magnification, and their coupling process, when they are isotropic. When they are not isotropic and there is a strong magnetic field, one can refer to both papers by Tsytovich and Kaplan. Now let me just say that there is however one particular worry about amplification. Amplification tends to pick out one mode. If modes are clearly distinguishable, and of that I am not so sure, then you are liable to get one mode (one hand of circular if you like) amplified by, say, $e^{30}$ and the other one amplified by $e^{28}$, say. In which case you get a very strong circularly polarized wave coming out because there is an $e^2$ between them. You do not need much difference between the amplification factors on two modes before you get full polarization, which of course is an advantage because we have got full polarization; the only trouble is that it tends to switch on one mode only and observation shows a smoothly changing elliptical polarization across the pulses. It is not all one mode as in the OH lines, for example. We have a beam of OH line coming straight towards us; it is circularly polarised; we are not allowed to look round the side of the beam but we have a strong suspicion it is going to be circular all over that beam. This is not the case here, so we should give attention to the mode selection process.

The coupling between plasma waves and radiation is greatest near the gyro-frequency, and the coupling can even be strong in directions which are perpendicular to the magnetic field. This means that there can be an amplification over a large solid angle and not just a small beam. It seems to me that in all these circumstances to try and construct a beam with these attributes by a diffraction-type process is hopeless because we have got such a wide range of wavelengths to deal with. Furthermore, in the Crab we have evidently got to do something rather similar in the optical range and the radio range to get our beam. And now I am going to describe a way of beaming the radiation which has nothing to do with any directive processes of amplification or diffraction, and which allows the radiation process to be nearly isotropic. I suggest to you that this process is nothing to do with electromagnetism, it is pure geometry. And the geometry that I am going to suggest to you is a pretty crude thing. It is already published (Smith, 1970); it does not tell you anything about the radiation mechanism but it does not need to. The radiator, a mass of plasma waves – porridge or kasha, or whatever the Russians would call it – is radiating out in all directions, and it is being driven round by the rotation of the pulsar on a radius 0.9 of the distance of the light circle; so it is moving at 0.9c. When it comes towards you you get a $\gamma^2$ amplification of the radiation and you get a pulse which looks as though it is a

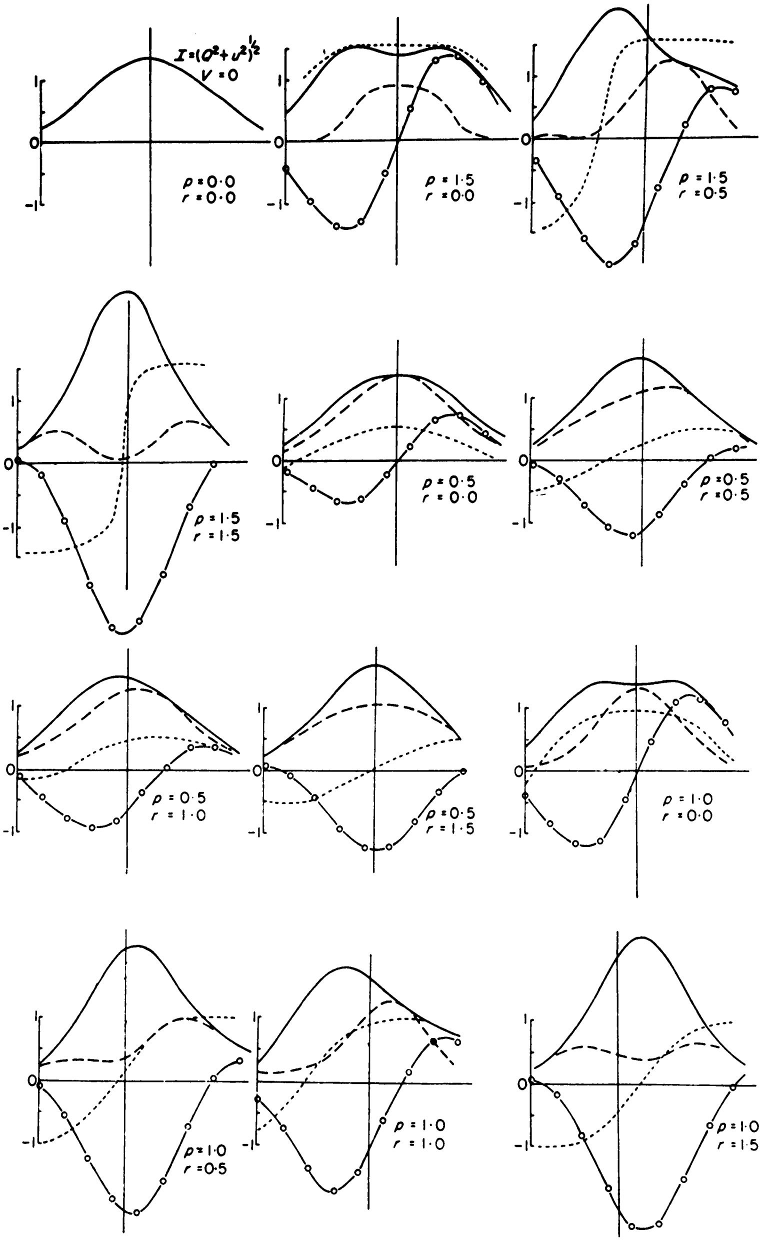

Fig. 3. Computed pulse shapes, using a cyclotron polar diagram and relativistic pulse formation. The parameters $I$, $V$, $(Q^2 + U^2)^{1/2}$ and $\tan^{-1} Q/U$ are shown for various orientations of the polar diagram relative to the pulsar rotation axis (from Smith, 1970).

directive radiation sweeping across you. The width depends on the gamma, i.e. on the $v/c$ ratio, but the shape is more or less independent of that. If you are not actually in the equatorial plane, you get a pulse of about the same width but not as high. You roughly get a beamwidth in the N–S direction which is about $1/\gamma^2$. If you add polarization to this you have a model of the radiator. My best model of the radiator is to take a circulating electron, or whatever it is, going round a magnetic field and just look at nearly isotropic radiation with the same polar diagram as cyclotron radiation. In fact I took the cyclotron polar diagram with a maximum of radiation at the poles (circular), and linear polarization at the equator. The whole thing is whizzing round the pulsar, but I do not know the attitude of it. I have got two parameters to find the direction of the pole in relation to the pole of the pulsar and I have explored all those parameters to produce theoretical pulse shapes, including Stokes parameters. These are published in my paper and some are shown in Figure 3. If you look long enough at an oscilloscope screen showing all the Stokes parameters you will find all the theoretical pulse shapes. I do not know that it really proves anything but it does, in fact, allow you to explain pulse shapes and polarizations with a polar diagram that is nearly isotropic, and this may be a help to theorists who wish to make a model of this most fantastic radiator.

## Reference

Smith, F. G.: 1970, *Monthly Notices Roy. Astron. Soc.* **149**, 1.

## Discussion

*M. M. Komesaroff:* Can your model explain the fact that, at least in the case of some pulsars, e.g. PSR 0833 – 45, the linear polarization is the same at identical phases of consecutive pulses, whereas the circular polarization, if present, must vary in a random way from pulse to pulse.

*F. G. Smith:* If the polarization is 100% then there can be virtually no circular polarization. This must be the case for PSR 0833 – 45. On my model it is possible to get linear polarization and no circular round one particular great circle of the emission polar diagram. Let the radiation to be emitted by a circular motion of an electron with an axis coinciding with the rotation axis of the pulsar, then the radiation from the equator will be linearly polarized with the same plane as seen from anywhere on the equator. Only a great circle which is inclined to the equator will contain any circular polarization. If the circular polarization is variable it means that its angle is variable, but that there is an average great circle which defines the linear polarization.

*A. T. Moffett:* I would like to point out that the emissivities and brightness temperatures encountered in pulsars are not staggeringly high by terrestrial standards. A large Klystron amplifier has peak emissivity of about $10^{12}$ W m$^{-2}$, and its brightness temperature might be about $10^{30}$ K if you look at its output waveguide.

*F. G. Smith:* This may not prove a thing but I suspect that you can obtain the same high energy densities also in micro circuits.

*F. D. Drake:* In considering the radiation mechanism, one must take into account the broadening of pulse width at lower radio frequencies, as observed in all pulsars at Arecibo. This effect, especially the observed increase in separation of peaks in a double peaked pulse shape, must be intrinsic to the pulsars in general, and so is not just an occasional peculiarity in behaviour.

More importantly, I think there is a compelling case that the particles are bunched. This of course automatically provides an amplification mechanism. As emphasized by Pacini, there are two basic frequencies present. The rotation frequency, 30 Hz, requires a quite unreasonable $\gamma$ to provide the observed frequencies. The gyro-frequency, some $10^{12}$ Hz, is too high to give any radio emission, but likely provides the optical and shorter wavelength radiation. To get the radio frequency radiation in your model, which is very close to Gold's, one must have the particles in bunches, whose scale is of the order of a metre, since these bunches sequentially radiate towards the observer as the velocity vectors sequentially point in that direction. The observed radiation field contains radio frequencies – this is a compelling argument for bunching.

Goldreich has recently shown that bunching will occur in a stream of radiating particles. The leading member of a proto-bunch, created by statistics, experiences a greater radiation reaction driving it to the rear. This process continues to produce a major bunching.

The presence of circular polarization may put no demands upon the emission mechanism. It could result from magnetoionic effects working on radiation initially linearly polarized.

*F. G. Smith:* I would first like to comment on the suggestion made by Gold that the radiation is generated by the peripheral motion of the electrons. In my model the radiation is not generated by the peripheral motion but it exists within the rotating frame of reference. The peripheral motion has the sole function of concentrating the radiation into a beam. I think there is a real difference between these two approaches. In my model the peripheral motion has a $\gamma$ of only 2½ or 3, whereas in Gold's model it must be some hundreds or more. The second point which you made suggesting that the gyro-frequency has nothing to do with the radio frequency is not obviously true. If the particles have very high energies then it may be that these are identical. It would, of course, be necessary to explain why the radiation is primarily at the gyro-frequency, but this may of course be due to the bunching.

You rightly emphasize the observed changes in pulse width which are most noticeable at low frequencies. I would, however, emphasize the opposite phenomenon that over a very wide range of frequencies above about 100 MHz, most pulsars show very little change in width.

Your final point concerning circular polarization does offer a possibility, but again I think that to invoke magneto-ionic theory will be very difficult since the polarization seems to be so independent of frequency.

*J. V. Jelley:* Your blob cannot surely be all that near to the velocity of light circle, because when viewed tangentially to the orbit, the pulse lasts say $^1/_{10}$ of the period. If this is the case, then for an orbit near the velocity of light circle, the true dimensions of your blob, in the rotating frame, will be a long arc in azimuth.

*F. G. Smith:* There are two different times to be considered. Firstly, the pulse window represents an arc which can contain a source of radiation. Secondly, a single isotropic source of radiation within this arc can give a pulse whose duration is determined by $\gamma$. The duration is in fact of the order $1/\gamma^3$ times the period.