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Pulsars and the Origin of Cosmic Rays [and Discussion]

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Pulsars and the origin of cosmic rays

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The distribution of pulsars and their main properties are discussed. Spin and magnetic fields provide them with the means of radiating radio pulses, and there are indications that these are due to relativistic particles radiating in magnetic fields. A contribution to the cosmic rays may be produced at the same time, especially by the youngest pulsars. On energetic grounds this could be a large contribution, but the composition expected would be predominantly iron, while the observed cosmic-ray abundances follow rather closely the general abundance distribution of most elements. The best suggestion at the present time is that the apparent shoulder in the general cosmic-ray spectrum seen around 10^{15} eV may represent the addition of the pulsars. In that case this feature should be mainly iron and its spallation products.

When in 1967 Miss Jocelyn Bell, working under the direction of Dr Anthony Hewish, discovered the pulsars, she projected us into a new era of high energy astrophysics and also of general relativistic astrophysics. The idea of the existence of neutron stars dates back to the work of Oppenheimer & Volkoff (1939) and of Landau (1932), and although there have been many interesting discussions concerning these stars at nuclear densities, it was not thought that astronomical tools existed for their detection. These earlier discussions ignored, however, the two features of the neutron stars that allowed them to signal their presence: their enormous rotational energy and the enormous strength of their magnetic fields.

In a contracting object in which the angular momentum is conserved, the moment of inertia decreases as the square of the factor by which linear contraction takes place (assuming homologous contraction), and the angular velocity therefore increases as the square of the contraction factor. The kinetic energy of rotation therefore also increases as the square of this factor. If, for example, one of the stars slightly more massive than the Sun, that rotates a little faster, were to contract to nuclear densities, the resulting kinetic energy of rotation (obtained through the work done by the gravitational field) would be of the same order as the entire store of nuclear energy that it possessed in the first place. In its second incarnation as a dense star it can now radiate in some new form as much energy again as it radiated in its entire lifetime as an ordinary star.

The contraction of magnetic fields leads to equally startling results. There the rule is, of course, that the magnetic flux linking any adequately conducting circuit will not change during contraction. The electrical conductivities of high density matter are indeed very high and satisfy this requirement with a large factor to spare. Thus, if a star of approximately solar dimensions possessed a field of 10^{-2} T before collapsing to nuclear densities, the linear contraction by a factor of 10^5 will then imply that the magnetic fields strength must go up by a factor of 10^{10} to maintain the flux linkage through any area. The resulting field would therefore be 10^8 T. These are surprisingly strong fields with which we did not have to reckon in the past, but there appear to be no reasons why they would not be created. The mechanical forces exerted by such fields are much weaker than the gravitational force in a neutron star, and the magnetostatic effects are thus quite negligible. Though detailed theories differ as to the radiation mechanisms that give rise to the observed pulses, they all agree that the precision of the timing, as well as the energy, is derived from the rotation, and that the mechanism is dependent on the very strong magnetic fields.

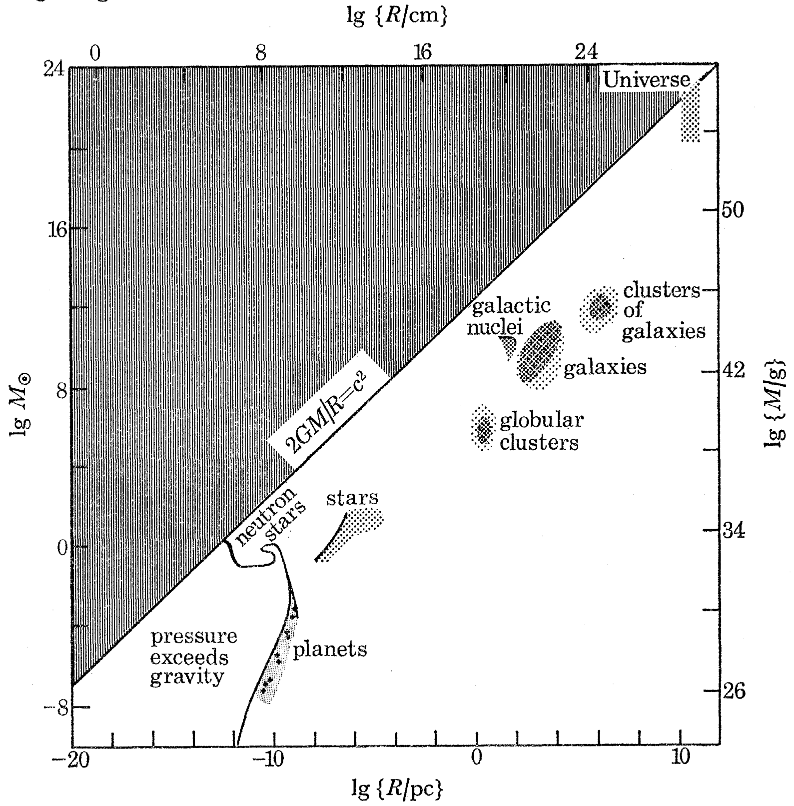

FIGURE 1. Mass against radius, plotted on a logarithmic scale, for astrophysical objects. Neutron stars are located extremely close to their gravitational radius.

These stars at nuclear densities can be set up only as a consequence of an implosion whose energy release has to be of the order of 10^{46} J. To see this, and also for general orientation, it is useful to see their location on a diagram relating the masses and radii of objects (figure 1). The upper left-hand half of the diagram concerns objects that have dissociated themselves from our world, being inside their gravitational sphere. The critical radius r for any mass M for creating the Schwarzschild singularity – or 'black hole', as it is now called – is given by the well-known relation that $2GM/r = c^2$ (where G is the gravitational constant, M the mass of the object, r its radius and c the velocity of light). The region on the mass–radius diagram where neutron stars are located is extremely close to the singularity. We know of no other objects, other than perhaps the entire Universe itself, that are located so close to the Schwarzschild singularity, although of course the recognition of neutron stars has greatly increased the interest in the search for objects that may have reached the singularity.

The important point for our present discussion concerns the stability line shown on the diagram, going up from cold matter at insignificant pressure, through matter in conditions such as our planets, and more or less smoothly up to white dwarf stars. This stability of cold matter is due to the pressure exerted by the electrons, and the nuclear material has no role other than to possess most of the mass and the neutralizing electric charge. However, the pressures that electrons can exert are limited, and this puts a limit to the mass that a white dwarf star can possess without its central pressure exceeding that value. (This of course was Chandrasekhar's famous discovery (1935).) Beyond a certain pressure the electrons will begin to disappear by joining protons in an inverse β decay process, and the electron pressure will then decline rapidly. Thus, as the density increases the pressure diminishes, and a star in that condition cannot resist collapse. Very soon after the onset of this collapse the internal pressure has become quite negligible, and the mass must then fall under its own self-gravitation towards its common centre at virtually free-fall speeds. This fall is arrested when the density becomes so high that pressures due to nucleons become important. This occurs at the density of the general order of 10^{13} or 10^{14} g/cm^3. Arresting this free infall then delivers an amount of energy which is of the order of 10^{46} J. This is a large amount by any standards, and even if only a small fraction of it gets converted into light, it could hardly be overlooked if it occurred in any one out of many thousand nearer galaxies. One feels sure that one can identify this with at least one type of supernova event (there could be other very violent stellar explosions due to other causes). The essential point is that a neutron star cannot possibly come into existence without an amount of energy of this order having been liberated in a sudden event. There is no way of changing over from electron pressure to nuclear pressure by a steady transition; it can only occur as a sudden event.

It was for this reason that one felt confident in the prediction that if pulsars were neutron stars they would be associated with supernova sites. The other predictions of the spinning neutron star model (Gold, 1968, 1969) were that the youngest pulsars should in general be expected to have the fastest pulsation rates, and that all pulsars should show on an average a lengthening of their periods. All these predictions have by now been established, first through the discoveries of pulsars in the constellation Vela and in the Crab Nebula. There is no reasonable doubt left that the basic nature of these objects has been established.

The very weak but long-range force of gravity must beat all the shorter range forces between nucleons when the mass is large enough. It is this, of course, that specifies the mass range of the neutron stars. The constants of nature are so adjusted that a small range of masses exists that makes stable neutron stars, which one might think of as giant nuclei. Beyond this mass range lies the Schwarzschild singularity. Just as the neutron stars can be thought of as nuclei, so the gravitational singularities can be thought of as elementary particles. They possess only very few quantities measurable from the outside, namely mass, electric charge and spin, and it is such simplicity that is generally regarded as the quality of an elementary particle.

Now I would like to discuss the role of rotation. Rotation is a great barrier against the contraction of matter on every scale. In the discussion of fast rotating neutron stars the problem is not why they are rotating fast, but how they could have been set up at all without excessive rotation preventing their formation.

Figure 2 demonstrates the state of affairs as regards rotation over the density range from the galactic gas density to the density of neutron stars. ω is the angular velocity of the contracting object considered, and ω_c is the critical angular velocity where the gravitational force on the equator is just balanced by the centrifugal force. Objects rotating with that angular velocity would flatten into a disk.

Starting from galactic densities we see first that an object of mass sufficient to condense into an ordinary star can in fact condense by only a small factor before its progress is arrested by spin. What happens then is not clear to astronomers. Differentially rotating disks of stellar masses may be common objects in the Galaxy, and we would not at present know how to look for them. Differential rotation can lead to friction, and therefore to an evolution, and it is clear that for the major class of initial mass distributions such friction would work to make mass to the inside of a particular radius lose angular momentum to mass lying to the outside of that radius. The inside contracts and the outside expands. Perhaps all kinds of instabilities take place also, making such disks produce not single stars, but the many pairs or multiple stars that we see. At any rate, it cannot reasonably be expected that galactic density gas can fall together to make a star without some intermediate process, and indeed probably a slow one, in which angular momentum is dramatically redistributed.

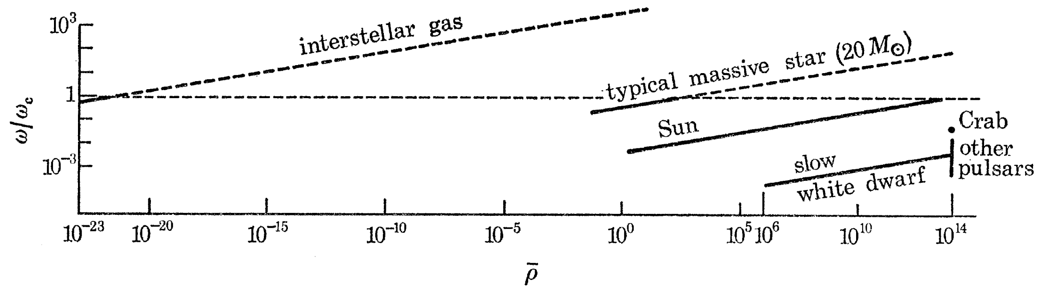

Figure 2. Ratio of angular velocity ω of an object to its critical angular velocity ω_c (at which the centrifugal force becomes equal in magnitude to the gravitational force) against the density $\bar{\rho}$ (g/cm^3) of the object. The sloping lines represent the path of an object contracting while retaining its angular momentum ($\omega/\omega_c = \bar{\rho}^{\frac{1}{6}} \times$ const.).

When we consider the higher density régimes, such as ordinary massive stars with their normal rotation speeds, we find also that they cannot contract much before reaching the critical angular velocity. Neither a neutron star nor even a white dwarf could be set up directly from the condensation of such an ordinary star, but again there must be intermediate stages with a major redistribution of the angular momentum. Small stars, like our Sun, must have suffered some very large loss of angular momentum so as to be moved far below the critical line, and such stars would in fact not be resisted by spin in the condensation all the way up to nuclear densities. But this is perhaps not important because they would in any case be arrested in the white dwarf configuration when all the internal energy is exhausted. The more massive stars have almost invariably much more angular momentum and must therefore go through intermediate phases in any collapse.

It has recently become known that there are white dwarf stars with remarkably low rotation speeds. One such star has been seen to have a regular variation in a spectral feature attributed to spin, of a period a little less than one day. For a white dwarf, as figure 2 shows, this is an extraordinarily low rotation speed and special circumstances have to be invoked for setting this up. The most likely appears to be that a degenerate core of a red giant star grew gradually, remaining more or less in rigid body rotation as the giant envelope expanded. Then a circumstance such as a nuclear explosion removed the envelope, and with it the bulk of the angular momentum; a slowly spinning white dwarf would be left over. The importance of this observation lies in the consideration that more massive degenerate cores might have grown in other similar circumstances where the envelope was not removed before the critical mass of the degenerate core was reached. In that case there would of course be a supernova explosion,

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removing the outer envelope in any case, but the core could now be expected to fall in, starting with a similarly anomalously low rotation speed. This process would produce a class of slowly spinning neutron stars and most likely of a rather well defined mass range, all defined by having started by reaching the critical mass of a degenerate core. There is a suggestion in the pulsar data that we can recognize such a class.

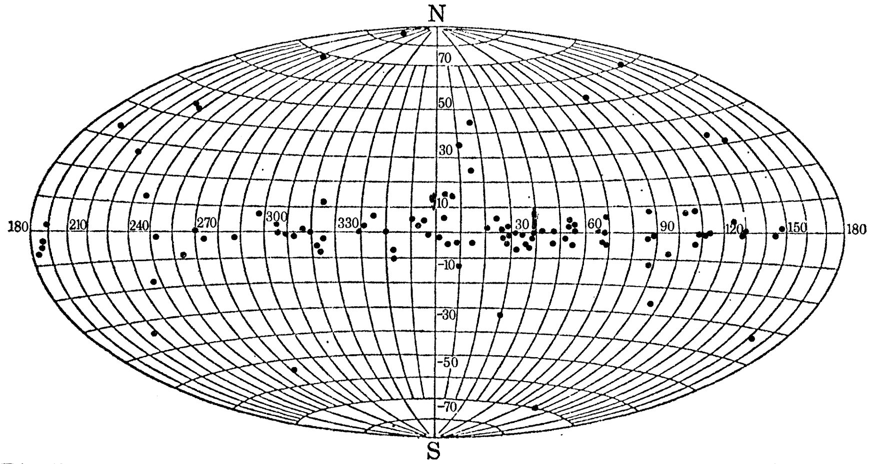

FIGURE 3. Distribution of pulsars in the Galaxy showing strong concentration towards the galactic plane.

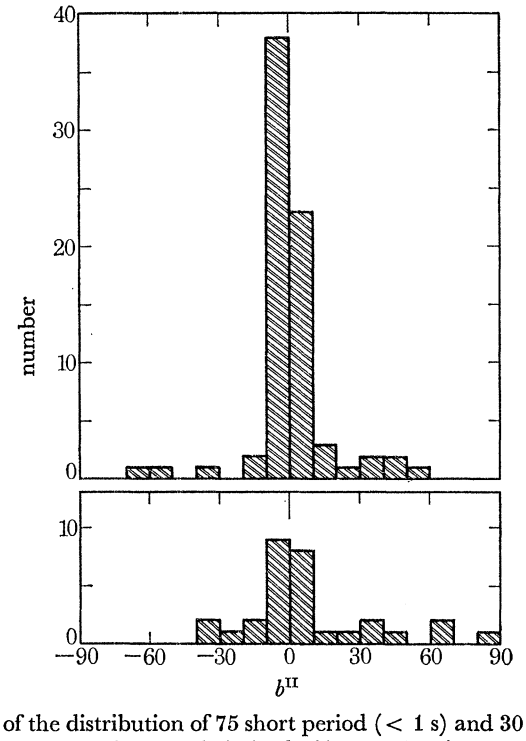

FIGURE 4. Comparison of the distribution of 75 short period (< 1 s) and 30 long period (> 1 s) pulsars in galactic latitude (August 1973).

Now let me turn to the more detailed knowledge of the pulsars. One hundred and five of them are now known. Their distribution in the Galaxy (figure 3) shows them to be strongly concentrated towards the galactic plane like the massive stars are known to be (which are assumed to be their progenitors). It is immediately clear from a comparison of the histogram of the galactic latitude of short period pulsars ($P < 1$ s) compared with that of the longer period ones ($P > 1$ s) that pulsars weaken greatly as their period lengthens. A factor of at least 100 is required by which the short period ones must be stronger, so that they are seen sufficiently far in the galactic sheet to appear so much more concentrated to the plane (figure 4), while the long period ones have a much wider distribution. The picture that has emerged from the properties of 105 pulsars is that there is a great deal of variation among them; but that on the whole they slow down and get weaker. The Crab pulsar has given a further indication of some importance: the luminous shell required 10^5 times the solar luminosity to be supplied in the form of electrons, of energy above 10^{11} eV in order that their synchrotron radiation can supply the observed polarized light. This supply of electrons has to be continuous since there are no reasonable circumstances that would allow the electrons to retain their energy for more than a few years at most. Thus, the thousand years since the observed supernova event is much too long a time for storage, and it has been clear that a current supply is required. When the pulsar and its period of $\frac{1}{30}$ s was discovered at the Arecibo Observatory, it was immediately a matter of great interest whether it would indeed show the expected slowdown, and if it did whether the amount would be compatible with the required 10^{31} J/s that needs to be supplied to make the luminous shell. Fortunately, the moment of inertia of neutron star models does not differ very much from the value 10^{44} g cm^2 (10^{37} kg m^2). The expected slowdown of the Crab pulsar was indeed observed, and the amount of energy loss per second, $I\omega\dot{\omega}$ (with the usual meaning of these symbols), corresponded closely to the 10^{31} J/s needed to supply the radiant energy of the shell. One inferred therefore that the neutron star's rotational energy was indeed made available to provide the energetic electrons in the cosmic ray range of energy ($> 10^{11}$ eV). For the first time one had a clear case of a cosmic-ray accelerator visible by astronomical means.

If one estimates the energy available in the Galaxy from the rotation of young neutron stars rotating initially near their critical speed, this will be of the order of 10^{45} J for each such star, or 3×10^{35} J/s mean supply rate if one such event occurred per 100 years. This is 30 times larger than the figure of 10^{34} J/s conventionally quoted as the requirement to maintain the galactic cosmic rays in the presence of a reasonable amount of galactic confinement. Therefore it seemed that pulsars could for once give an adequate energy source for the main supply of cosmic rays, as well as providing a clear demonstration that an acceleration mechanism existed there.

But there are other problems that argue against the pulsar origin for most of the cosmic rays. It is difficult to see any way in which the ordinary abundances of the elements would be available in a zone subjected to the extreme circumstances of a supernova explosion. If the material was drawn out of the surface of a neutron star, it would be close to material at pressures at which nuclear equilibration would occur readily. Thus, however the material is supplied in the vicinity of a pulsar, it ought to show a sharp concentration towards iron and its spallation products, and in no case could it mimic the abundances of elements generally available in the galactic mix. Yet the cosmic rays clearly show at least a major component to possess the ordinary galactic abundances. If no escape from this argument can be found, one cannot hold the pulsars responsible for the majority of the cosmic rays, although of course they might provide some additions. One will have to see whether electrons or extra iron peak elements in a certain energy range can be ascribed to pulsars.

There are several processes that one thinks will take place in the vicinity of a pulsar. First, there is the generation of electric currents by the homopolar dynamo effect. Since the pulsar is rotating with a strong magnetic field, and since it is electrically connected (through however tenuous a plasma) to a region of space whose plasma content cannot be in co-rotation, an e.m.f.

is generated around any circuit connecting different latitudes on the star through distant parts of the external plasma (figure 5). The important conclusion is that such circuits would have enormous voltages applied to them by this effect. The conventional values for fieldstrength, size and spin of the star result in voltages of the general order of 10^{18} V. This does not mean that any particles of 10^{18} eV energy will be produced; all it does mean is that a current will flow unless there is an insulator interrupting the circuits, capable of withstanding such voltages without breaking down. No such insulating materials can be envisaged. This effect has been investigated by Goldreich & Julian (1969) who were able to make conclusions concerning current densities and the slowdown law of the pulsar that would result.

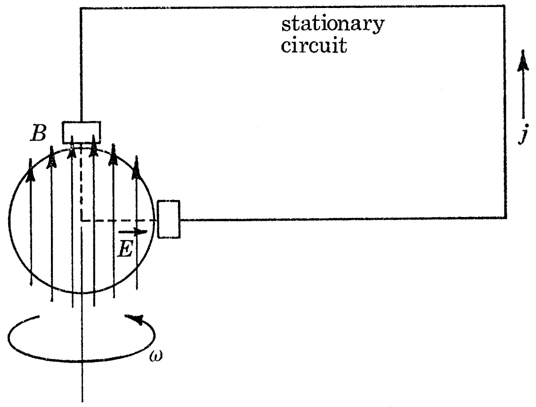

FIGURE 5. Pulsar as a homopolar dynamo.

Secondly, there is the radiation at the basic rotation frequency, if the magnetic field has a transverse component. This has been investigated by Pacini (1968) and by Gunn & Ostriker (1969).

Both these processes draw energy out of the rotational kinetic energy of the star. In either case some part of this energy could reappear in the form of relativistic particles through the action of some intermediate process. A number of such processes have been discussed, but it is not yet clear whether any of them must really be expected to occur.

Another process that is expected to be occurring is the co-rotation of the plasma out to a certain distance from the star. The plasma adjacent to the pulsar's surface will be maintained in rigid body rotation with it, and this effect may persist out to the region where co-rotation would imply motion at the speed of light. (The 'velocity of light cylinder' as we have called it.) Beyond this, co-rotation can of course not be present. It is possible that on fieldlines that close just within the velocity of light cylinder, particles may achieve a high energy; but one would estimate that this energy cannot reasonably exceed 10^{14} eV per nucleon with the conventional choice of parameters. Another process that may occur is the annihilation of magnetic field wound up around the exterior of the velocity of light cylinder (figure 6). There the plasma possessing some field from the pulsar cannot follow the rotation, and the fieldlines must thus be trailing, and they must be spinning a cocoon, so to speak. The magnetic pressure resulting from this wound-up field must cause it and the local plasma to expand. However, in the equatorial plane fieldlines of opposite direction will be pressed towards each other and will there annihilate at a rate limited only by the available plasma pressure. This annihilation may also produce a stream of accelerated particles in a tangential direction, forward in the sense of rotation.

We have no way of deciding at the present time which of these possible effects is the dominant one, either for producing the radio and optical pulses, or for producing relativistic particles. But the general order of magnitude of the fieldstrengths and the dimensions concerned suggest in each case that energies much higher than 10^{14} eV/nucleon (or a few times 10^{15} eV for heavy nuclei) would be unlikely. This conclusion cannot be avoided by supposing yet stronger magnetic fields to occur, for then the production of high energy photons would become excessive. The considerations are rather similar to the ones that would decide on the energy limit of a synchrotron accelerator, given its physical dimensions.

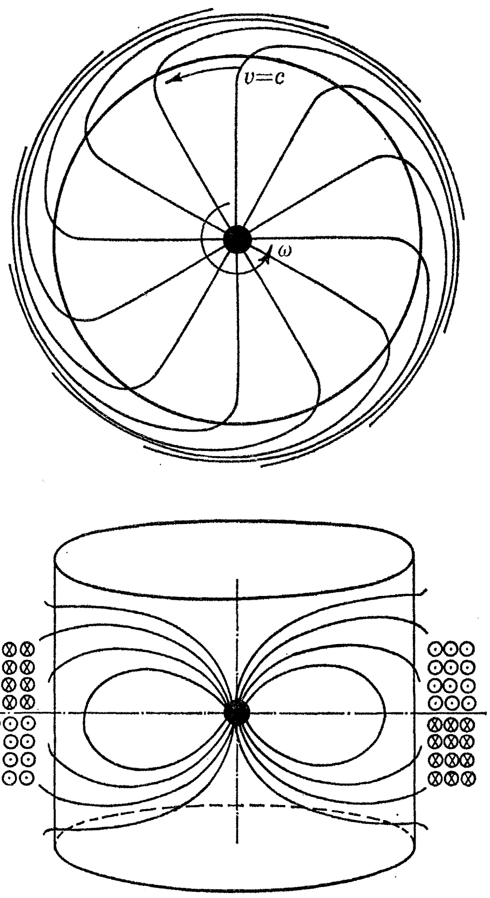

Figure 6. Winding up of the magnetic field lines outside the light cylinder (top and side views).

On this basis a contribution from pulsars would not be likely to have as steep a spectrum as the general cosmic rays. One observes the radio pulses to show very little increase in pulse length at the lower radio frequencies and from this one could conclude that the relativistic particles responsible for this radiation did not have a very steep spectrum. If they had, then the lower energy particles would dominate for the contribution at the lower radio frequencies and they would necessarily radiate a wider beam, which would be transformed into a longer pulse length. Perhaps one can take this indication to mean, as one might otherwise expect also, that the pulsar accelerating machine puts most of its energy into a rather narrow spectrum. Contributions from different pulsars would of course not be exactly alike, and although this would somewhat increase the spectral width of the pulsar contribution, it might still be expected to

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show up as a rather narrow addition, preferentially of the iron group of elements (and its spallation products) at an energy around 10^{15} eV. It is most interesting to note that there is a shoulder claimed to be observable in the cosmic-ray spectrum, followed by a steeper spectrum at higher energies (see other papers presented at this symposium). It will be most interesting to analyse this feature further to see whether it perhaps represents the pulsar contribution.

References (Gold)

Chandrasekhar, S. 1935 *Mon. Not. R. Astr. Soc.* **95**, 207.
Gold, T. 1968 *Nature, Lond.* **218**, 731.
Gold, T. 1969 *Nature, Lond.* **221**, 25.
Goldreich, P. & Julian, W. H. 1969 *Astrophys. J.* **157**, 869.
Gunn, J. E. & Ostriker, J. P. 1969 *Nature, Lond.* **221**, 454.
Landau, L. 1932 *Phys. Zeits. Sowjetunion* **1**, 285.
Oppenheimer, J. R. & Volkoff, G. M. 1939 *Phys. Rev.* **55**, 374.
Pacini, F. 1968 *Nature, Lond.* **219**, 145.

Discussion

F. G. Smith (*Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire*). It is by no means sure that the full potential difference of the homopolar generator will be available for particle acceleration, since the magnetosphere so arranges itself as to cancel out most of the voltage. It is equally uncertain that very high energies can be assigned to the particles responsible for the pulsed radiation; Gold's interpretation depends on an assumption about the location and nature of the emission process which is not widely accepted.

A. W. Wolfendale. Although heavy nuclei may be accelerated efficiently by pulsars will not many of these nuclei be fragmented in the intense radiation fields surrounding the objects?

T. Gold. The amount of fragmentation of heavy nuclei accelerated in the vicinity of pulsars might not be so much as one would think at first if all the photon flux responsible had very much the same direction as the energetic particles. Of course some fragmentation could occur, but as we know the distribution of elemental abundances could not be accounted for just by the photo-spallation products of iron. If the pulsars make a contribution, it should be recognized as an additional iron peak, plus a certain augmentation among the spallation products of iron.