F. PULSARS, COSMIC RAYS AND BACKGROUND RADIATION

(Edited by M.J. Rees)

SOME ASTROPHYSICAL ASPECTS OF PULSARS

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1. Formation Rate of Pulsars

In principle the formation rate can be obtained on the basis of a knowledge of a spatial densities and lifetimes. Extreme care is needed, however because of the incompleteness of the available sample because of luminosity effects. Since luminosity and age are correlated it is essential that densities and lifetimes be evaluated for the same sample. Incompleteness affects the very faint pulsars most strongly, but because of their long lifetime the effect on the formation rate is comparatively small. We shall assume that the lifetime of a pulsar in our sample is on the average equal to twice its age. Further we estimate distances (r) from dispersion measures on the basis of a mean electron density n_e of 0.05 cm^{-3} near the Sun. The fluctuations in n_e again may cause systematic errors, but no information is available for an estimate of the magnitude of these.

There are 5 pulsars known with $r \cos b$ (b galactic latitude) less than 100 pc. For three of these ages are available from which a harmonic mean life time T of 2.5×10^7 yr is found. Of 19 pulsars with $r \cos b < 300$ pc, eight have ages from which $T = 1.1 \times 10^7$ yr. Samples with larger $r \cos b$ appear to be too incomplete for our purpose. Taking the Galaxy to be a uniform disk with a radius of 14 kpc, we obtain from both samples a formation rate of about one pulsar per 250 yr. It should be stressed that this is the rate for 'visible' pulsars. If beaming effects cause only a fraction η to be in principle observable, the formation rate is to be multiplied by η^{-1}.

2. Supernovae and Pulsars

Current estimates of the supernova rate in our Galaxy based on supernova remnants yield values of the order of one SN per 60 yr, which with the pulsar rate derived above corresponds to one 'visible' pulsar per 4 SN. The fact that 12 supernova remnants within 2 kpc contain 2 pulsars is not incompatible with this estimate. Since beaming effects are likely to be important and values of η of the order of $\frac{1}{4}$ not unreasonable, the data seem to lend some support to the idea that there is a one to one correspondence between supernovae and pulsars, at least in so far as the disk type supernovae are concerned. Because supernovae seem to represent a final evolutionary phase of many upper main sequence stars, we probably can take the pulsars to be a fairly representative sample of the inner regions of such stars.

3. Stellar Magnetic Fields

If pulsars are slowed down mainly by electromagnetic torques their surface magnetic fields can be estimated to be of the order of 10^{12} G with a surprisingly small scatter

De Jager (ed.), Highlights of Astronomy, 725–726. *All Rights Reserved*

of a factor of about 3 either way. Because of the high conductivity these fields are likely to have evolved with conservation of flux; in this case we may estimate the field strength in the deep interior of upper main sequence stars to be of the order of 100–1000 G. Stars somewhat lower down the main sequence evolve into white dwarfs, for which if initial conditions are similar, surface fields of the order of 10^6 G would be expected. Searches have been made for such fields. One white dwarf has been found by Kemp, Swedlund, Angel and Landstreet to have strong circular polarization which may perhaps indicate a field of 10^7 G, but in a dozen other white dwarfs Angel and Landstreet have established upper limits, sometimes as low a 10^4 G.

The interpretation is still uncertain. It may be of course that stars lower down the main sequence and without convective core have only very weak fields; alternatively convective or other motions in white dwarf atmospheres could conceivably cause an existing field to be unobservable.

4. Pulsars and Cosmic Rays

The production rate of cosmic rays, required to maintain a steady state in the galaxy can be estimated as 6×10^{40} erg/sec or 10^{50} erg/supernova, if supernovae are responsible. The maximum rotational energy of a pulsar is 10^{53} erg and because the electromagnetic fields associated with rotating magnetic objects can accelerate particles rather effectively, it is tempting to assume that the pulsars are in the prime sources of cosmic rays. However *if* the Crab Nebula pulsar were representative for the class some difficulties could arise:

(a) The slowing down rate of the pulsar indicates that if the initial rotational energy had been close to the maximum permissible value, a good fraction of the energy would have to have been radiated in gravitational waves, leaving only several times 10^{51} erg in 'useful' energy.

(b) The acceleration of the filamentary shell (assumed to have a mass of 1 $M_\odot$) shows that the total production of confined particle energy cannot have been much larger than 10^{49} erg. This would be consistent with an initial rotation rate much less than the maximum. This is compatible with the slowing down rate if gravitational radiation has been negligible.

(c) A comparison of the current loss of rotational energy with the energy requirement for the Nebula indicates that the ratio of electron energy to total particle energy hardly can be less than about 0.2 and may be larger. The situation is clearly different in the cosmic radiation observed near the Earth.

In addition the composition of the surface layers of pulsars presents some problems. Neutron stars are believed to have envelopes of heavy elements in contrast to the cosmic rays which are mainly protons and α-particles. Perhaps the pulsars accelerate only heavy positive particles and electrons while other objects account for protons and the lighter nuclei. While such a possibility cannot be excluded the near identity of the energy spectra of the different constituents of the cosmic radiation might then be difficult to explain.