INTRODUCTORY REVIEW

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ABSTRACT

     In this review my aim is to mention very briefly the present state
of knowledge over a wide area in order to provide some focus for the
wealth of information that this symposium will bring forth.   During 13
years a great deal has been discovered, but the jigsaw puzzle of the
pulsar model is still in pieces.   Some of these have intriguing shapes
and seem to fit together, but they do not yet indicate what the picture
will be.

1.   THE PULSAR POPULATION

     Surveys of the northern and southern skies have now revealed at
least 328 pulsars.   Distances estimated from dispersion measures,
assuming a simple model for the mean electron density, and making
allowance for known HII regions, show that most pulsars lie within a
few kpc of the sun.   The surface density of the galactic disk increases
within a radius of 10 kpc and reaches a maximum at about 6 kpc similar
to the distribution of supernova remnants.   Pulsars are concentrated
towards the galactic plane with a scale height of about 400 pc.
Accurate positional measurements, using interferometry and pulse-timing,
have enabled proper motions of the order 10-50 m arcsec y^{-1} to be
obtained.   When combined with known distances these lead to typical
spatial velocities of the order 180 km s^{-1} with vectors directed away
from the plane as expected.   Assuming an average z-component velocity
of $\sim$ 100 km s^{-1} pulsar lifetimes cannot exceed about 4 x 10^6 y without
conflict with the observed scale height of 400 pc.   This is signifi-
cantly shorter than lifetimes derived from spindown in many cases and
implies that the stellar magnetic field decreases with time – a feature
that is also required to account for the P-$\dot{P}$ distribution as discussed
later.

     The radio luminosity distribution appears to be flattening at the
lowest luminosities so that the overall population can be roughly
estimated.   The total count, assuming circular symmetry and also that

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four pulsars in five are unobserved on account of beaming is
$(5 \pm 2) \times 10^5$.   This population requires a birthrate of about one
pulsar in 10 y, and is uncomfortably large in comparison to the observed
birthrate of supernovae in our galaxy.   It is clearly important to
refine the parameters involved in the total count in view of its impli-
cations for the progenitors of neutron stars.

Only two pulsars have been found in binaries.   These have binary
periods of $7^h 45^m$ (the famous short period pulsar of great interest in
general relativity) and 1265 day.

2.   PULSE TIMING

Observed pulse periods lie in the range $0.03 < P < 4.3$ s.   The
distribution, which cannot be seriously affected by selection, rises
steeply to a peak at about 0.5 s and has a median ~ 0.8 s.   Values of
the spindown $\dot{P}$ are known for at least 226 pulsars and span a wide range
$10^{-18} < \dot{P} < 10^{-12}$ s s^{-1} with a median $\sim 3 \times 10^{-15}$ s s^{-1}.   A meaningful
second derivative $\ddot{P}$ has been obtained only for the Crab pulsar.   In
other cases timing irregularities are large enough to obscure second
derivatives.   Sudden decreases of period (glitches) have been found in
4 pulsars.   Vela (4 jumps, $\Delta P/P \sim 2 \times 10^{-6}$), PSR 1641-45 and PSR 1325-43
(1 jump each, $\Delta P/P \sim 10^{-7}$), Crab pulsar (2 jumps, $\Delta P/P \sim 10^{-8}$-10^{-9}).   The
Crab and Vela are young pulsars in which jumps are expected to occur
more frequently.   The limited statistics of the present sample suggest
that typical older pulsars undergo roughly 1 jump in 50 y.

For the Crab pulsar jumps in period can be understood in terms of
starquakes in a rigid crust-superfluid core model.   The larger jumps
in Vela have been discussed in relation to rigid core models but diffi-
culties have led to more complex ideas concerned with the crustal
pinning of quantised vortex lines in a superfluid interior.

Data for 37 pulsars timed over 8 years show some instances where
timing residuals, after allowing for $\dot{P}$, fall within the observational
uncertainty of ~ 0.2 ms, corresponding to a stability of 1 in 10^{12}.
This is close to the limit where scintillation data indicate that inter-
stellar density variations may cause problems unless corrected for by
dual-frequency measurements.   In many other cases pulsars exhibit
residuals, larger than the observational uncertainty, which vary
randomly from year to year.   The physical significance of these is not
yet clear but they should contain useful structural or environmental
information concerning the neutron star.

The distribution of $\dot{P}$, plotted against P, shows an interesting V-
shape which has been interpreted as temporal decay of the neutron star
magnetic field.   On dipole models of magnetic braking the surface field
strength B is such that $B^2 \propto P\dot{P}$, and the pulsar age $\propto P/\dot{P}$.   Plotting
$P\dot{P}$ against $P/\dot{P}$ the evolutionary tracks of individual pulsars would
follow horizontal lines if B remained constant.   The tracks would
curve steeply downwards if B decreased with age and the observed dis-

tribution can be fitted quite well if B decreases exponentially on a timescale of 0.2×10^6 y. The distribution also suggests that pulsars must cease to radiate when their evolutionary tracks cross some boundary line. The relation $\dot{P}P^{-11/4} \sim 10^{-15}$, which is the threshold predicted for electron-positron pair production, is a reasonable fit. That pulsars spending a significant fraction of time in a 'nulled' state have points near this line gives added weight to the concept of abrupt extinction at the boundary line.

3. LUMINOSITIES AND SPECTRA

Pulsars have radio spectra of the form $\nu^{-\alpha}$ where, typically, $1 < \alpha < 2$. Low frequency turnovers sometimes occur for $\nu < 1$ GHz and spectra often steepen for $\nu > 1$ GHz. Radio energy accounts for but a small fraction of the spindown energy $I\Omega\dot{\Omega}$ of the neutron star, typical fractions being 10^{-3} to 10^{-8}. The Crab and Vela pulsars have even smaller efficiencies at radio frequency and emit most of the pulsed energy in γ-rays at efficiencies of $\sim 10^{-2}$ to 10^{-3}. These two sources also emit optical pulses at efficiencies of $\sim 10^{-5}$ (Crab) and 10^{-9} (Vela). Unlike the radio spectrum, where pulsars show large intensity variations on many timescales, the optical - γ radiation is extremely steady. Over 7 years one component of the optical pulse of the Crab may have decreased by about one per cent. The high frequency spectra lie well above the extrapolated radio spectrum indicating that different radiation regimes must be involved.

4. PULSE CHARACTERISTICS

The time-averaged pulse shapes across the whole spectrum make an interesting comparison for the Crab and Vela pulsars. The close synchronism of the main pulse components in the Crab is not repeated for Vela, but the bridge of emission across the pulse centre is a shared feature of the optical and γ-ray pulses in both. As in other pulsars which display widely spaced main pulse components, it is debatable whether the two peaks are due to a single broad beam with high intensity at its edges, or to a pair of narrow beams pointing in nearly opposite directions. In pulsars as a whole the histogram of component separation extends continuously out to 180°, with no tendency to rise at 180°.

At radio wavelengths pulsars display a rich variety of behaviour on many timescales, but the average pulse profiles remain constant. The overall pulse-width is about 10° in longitude. About 25% of the sources exhibit double-peaked, or more complex profiles, complexity becoming more common at larger values of P; the peak separation (in longitude) tends to increase as P decreases. The separation is also frequency dependent, varying as $\nu^{-0.25}$ for $\nu < 1$ GHz and remaining almost constant for $\nu \gtrsim 1$ GHz.

Individual pulses are strongly polarized, usually linearly, with a systematic swing of position angle varying most rapidly at the pulse centre. This is in good agreement with the polar beam (rotating

vector) model.   The simple pattern persists, even when the pulse
profile is highly complex, but it is often masked by the presence of
two radiation modes having nearly orthogonal position angles.   Each
mode, on its own, follows the simple pattern but one or other of the
modes dominates over specific ranges of longitude.   Strict orthogo-
nality is not always observed and modes separated by 65° - 90° in
position angle are found.   Circular polarization, when present, often
maximises at the pulse centre or reverses its sense there.   This again
agrees with the polar beam model.   The degree of polarization usually
decreases at higher frequencies and can vary by $\stackrel{<}{\sim}$ 2 between 100-430 MHz.

Within individual pulses the intensity is modulated on various
timescales, the relative importance of which changes markedly across
the radio spectrum.   The subpulse regime has a timescale $\sim$ 5 x 10^{-3} P
and the microstructure a scale of $\stackrel{<}{\sim}$ 5 x 10^{-4} P.   The correlation of
both with P is approximate but significant.   Microstructure is
occasionally quasi-periodic (Q $\stackrel{<}{\sim}$ 10) with period $\sim$ 10^{-3} P.   Subpulses
often exhibit a systematic drift in longitude, from pulse to pulse,
which modulates the intensity at a given longitude with period P_3.   The
drift rate can be highly regular or variable.   Usually P_3 $\sim$ a few times
P, but values up to 40P have been observed.   Intensity variations due
to microstructure and drifting subpulses are mainly low frequency
phenomena and decrease rapidly above about 1 GHz.   By contrast, the
integrated pulse intensity shows increasing pulse to pulse variations
at frequencies above 1 GHz.

Two further important effects are nulling and mode-switching.
Nulling is an abrupt cessation of radiation at all frequencies which
typically lasts for a few seconds but may endure for hours.   Pulsars
with substantial nulling (> 5% of total time in null state) have
$\dot{P}P^{-11/4}$ $\sim$ 10^{-15} and may be near some radiation threshold.   Mode-
switching is an abrupt change of pulse profile which may also entail
changes in the subpulse and drifting behaviour.

Drifting, nulling and mode-switching are distinctive phenomena
which must severely constrain any theory of pulsar radiation.
Especially dramatic and clear-cut cases deserve close attention.   For
example, PSR 0809+74 shows a remarkable connection between nulling and
drifting which would be hard to discern in a less regular drifter.   At
low frequencies this source emits all its radiation in drifting sub-
pulses for which P_3 = 11P with Q $\stackrel{>}{\sim}$ 500 (an observational limit).   Nulls
are quite frequent and the first pulse to appear at the end of a null
exhibits subpulses at the same longitudes that they occupied when the
radiation ceased, although the subpulses can be located anywhere within
the pulse window.   The subpulses 'remember' where they were for up to
13 s (the longest null observed).   Immediately following a null the
drift rate is slightly slower and takes a few seconds to recover its
normal rate.   Observations made simultaneously at 102 and 1720 MHz
have shown that the drift rate at 1720 MHz is almost twice as slow as
at 102 MHz although P_3 remains the same.   The subpulses at each
frequency appear to be physically related since their intensity

variations are significantly correlated, even though their instan-
taneous longitudes are usually different.

     Another notable pulsar is PSR 1237+25 which has a 5-component
profile with approximate mirror symmetry about its centre.   The two
outermost components are strongly modulated, in antiphase, with
P_3 = 2.8 P, while the three inner components show no periodic modula-
tion.   In terms of the polar beam model three separate conical
beam systems appear to be involved.   A system of excitation zones
spiralling inwards has also been suggested.   Finally PSR 1822-09
deserves mention on account of its intriguing connection between mode-
switching and drifting subpulses.   In one radiation mode two subpulses
are present, one of which shows occasional drifting with P_3 = 11P;   in
the second mode one subpulse vanishes and the other shows well-defined
drifting with P_3 = 40P.

5.   PULSAR MODELS

     Rapidly spinning neutron stars are believed to be surrounded by a
corotating magnetosphere in regions where magnetic field lines form
closed loops inside the velocity of light cylinder.   The local charge
density is assumed to adjust itself until $\underline{E}.\underline{B}$ = 0 in the rotating frame,
hence generating a density $\propto \underline{\Omega}.\underline{B}$.   This assumes that charges of either
sign can be drawn freely from the surface and that there are no diffi-
culties in populating field lines along which the charge density changes
sign.   'Open' field lines, which intersect the light cylinder, are
taken to be regions where $\underline{E}.\underline{B} \neq 0$ and along which charges may suffer
large acceleration.   Whether charges leave the star through the light
cylinder or lose energy via radiation and return to the star along
different field lines is under debate.   In the former case a stable
flow requires charge balance and the difficulty arises that open field
lines are preferentially associated with charges of one sign only.

     Until these atmospheric problems have been solved it may be rash to
consider detailed radiation mechanisms.   At present most attention is
given to models in which the radio emission is generated not far above
the polar caps, at heights of less than about 10^3 km.   A substantial
fraction of the voltage arising from unipolar induction across the polar
cap is assumed to be available for accelerating charges along open field
lines close to the stellar surface.   This could be the case when E is
not strong enough to draw + ions from the star in the vicinity of the
polar cap and if $\underline{\Omega}.\underline{B} < 0$.   An electron in this region accelerates
violently towards the surface, its spiral motion along $\underline{B}$ generating γ-
radiation which subsequently initiates electron-positron pairs.   Repe-
tition of this sequence generates a particle-cascade, positrons moving
outwards and electrons inwards.   Local heating of the surface due to
electron bombardment could be sufficient to release ions by thermionic
emission, and their subsequent interaction with thermal X-rays from the
hot-spot could generate further pairs, the final result being a
sustained electron-positron discharge.   Beyond the acceleration zone a
relativistic outflow of electron-positron plasma (Lorentz factor $\stackrel{<}{\sim}$ 200)

might be penetrated by both an ion stream (Lorentz factor ~ 500) and a positron stream (Lorentz factor $\sim 10^6$). The motion of ions through the e^{+-} plasma could generate two-stream instabilities rapidly enough for charge-bunching to occur, finally leading to the emission of radio waves by coherent curvature radiation. The radiation would be emitted tangentially to B on open field lines at distances around 10^2-10^3 km from the surface.

It has also been suggested that radiation could be generated close to the light cylinder, which has a radius of $\sim 10^5$ km for a typical pulsar, but no detailed physical models have been outlined. No direct observational evidence can yet determine the site of the radiation zone. For polar-cap models involving narrow-band coherence the radiation at higher frequencies is emitted lower down. This would lead to a temporal retardation factor $\Delta t \sim \Delta R/C$ where ΔR is the difference in height of the radiation zones at two frequencies. If the charge bunches co-rotate aberration would also occur, but there seems to be no reason why the relativistic outflow should partake in corotation. Observations of pulses at different frequencies have not shown retardation so that any separation of the sites of high and low frequency radio emission must be less than about 100 km.

On general grounds it is hard to see how the complex behaviour associated with mode-switching and drifting subpulses (including the memory effect) could be sustained near the light cylinder. At large distances there are also problems in maintaining a constant polarization profile when the radiation field may exceed the stellar magnetic field. The polar-cap model appears to provide a suitable environment to explain the polarization and pulse profiles. The increase in width of the profiles at lower frequencies and drifting subpulses (in particular PSR 0809+74 observed at widely different frequencies) lend support to the idea of streaming along field lines which generates different frequencies at different heights. On the other hand the mechanism of drifting is hard to understand. Plasma drift in ExB fields has been suggested, and the thermal time constant of hotspots on the surface has been invoked to explain the drifting subpulse memory. If the revival of discharges after a null is due to thermionic emission of ions from hotspots it seems that the time constant must be chosen with care. It must be long enough to survive nulls of up to 13 s, but short enough to avoid initiating a discharge around the entire annulus under normal drifting, when the circulating hotspots travel a distance equal to their separation in about the same time.