PULSAR, PULSAR, PULSAR...

When astronomers first discovered pulsars, the regularity of the radio pulses put out by these objects led to a not entirely facetious suggestion that alien intelligences might be directing the signals. One wonders that the writers of some starship epic haven't used it yet: A system of radio navigation beacons scattered around the galaxy, each identifiable by its pulse shape and frequency. But then radio navigation is probably too old-fashioned. The immediate criticism of the little green people theory of pulsars was that any *intelligent* aliens wouldn't muck around wasting all that energy on a signal when there are cheaper ways of doing it.

The pulsar phenomenon was left to material causes, which are often more lavish, more complicated and exhibit less planning than most exercises of volitional intelligence. "People say studying pulsars is like studying the sun," says James M. Cordes of Cornell University, speaking at the recent meeting of the American Astronomical Society in Calgary, "there are so many things going on we'll never figure it out. I don't think that's the case." And he went on to review the present state of understanding.

First he gave some numbers. There are 330 known pulsars—radio pulsars, that is. Three of these are known to be in binary star systems. Although it is pretty generally accepted that the core of the pulsar phenomenon is a neutron star and that neutron stars are formed by supernova explosions, only two pulsars, the Crab and Vela, are located in identifiable supernova remnants. The average distance of pulsars from the galactic plane is about 350 parsecs. Their velocity perpendicular to the line of sight (proper motion) averages 560 kilometers per second.

The last figure combined with data on pulse periods can lead to a birth rate for new pulsars. The periods of known pulsars range from 33 milliseconds for the Crab to a maximum of 4.2 seconds. Above one second the number of pulsars with longer and longer periods drops rapidly to zero. Observation shows that pulsar periods are gradually slowing down. Therefore pulsars must shut off permanently after some time, say a few million years. Otherwise there would be a population of pulsars with very long periods (10 minutes or more). There aren't.

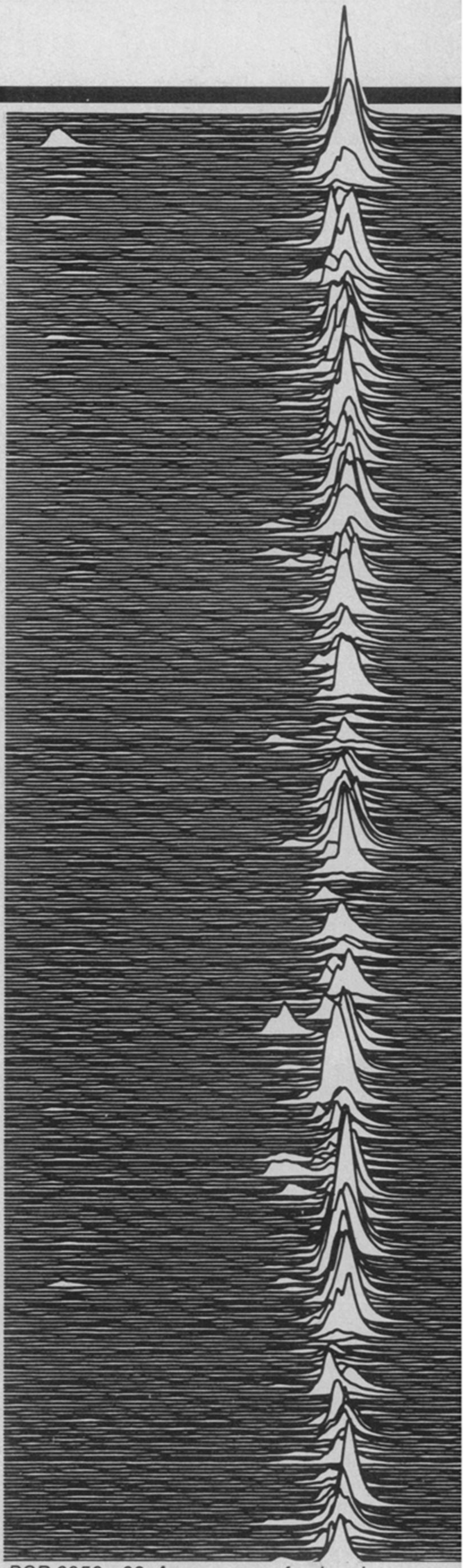
From the average motion of pulsars across the line of sight, an average motion perpendicular to the galactic plane can be calculated as a simple matter of geometry. The result is 100 kilometers per second. Combining this with the mean distance from the plane of 350 parsecs, yields a mean age of 3.5 million years. (This reasoning is based on the assumption that pulsars are born in the galactic plane and given a kick in some direction or other by the supernova explosion that makes them.)

How many pulsars might there be in all? Applying the statistics of all-sky surveys to the sample known yields a supposition that there are about 100,000 pulsars potentially observable from earth. That is, their radiation is beamed toward earth. (All models have assumed that pulsar radiation is beamed. It's an easy way to account for the pulses, and compared to models that would have radiation as bright as the average pulsar being emitted into a full sphere of volume, beamed models drastically lower the total energy requirement.) There must also be pulsars not beamed toward the earth. What factor to put for them is something of an educated guess, but 5 or 10 seems reasonable. So there may be a half a million or even a million pulsars in our galaxy. "We can imagine that there are a lot of pulsars we don't see," Cordes says.

From these statistics pulsar birthrates necessary to keep the observed number of active pulsars replenished can be calculated. If beaming is not taken into account, about one pulsar birth every 180 years is necessary. If the corrections for beaming are included, the figure ranges from one in 20 to one in 60 years. These are more comfortable figures, Cordes says, than those that prevailed 10 years ago. At that time the number of pulsars actually observed was much smaller than the present number. This smaller sample, when statistically extrapolated led to a much faster birthrate, about one in 5 years. This seemed to be an impossible figure. Supernovas are just not observed in the galaxy that often. At the time, theorists looked for ways of making pulsars that don't involve supernovas. Today's birthrates are more comfortable for supernovas.

Today's standard pulsar model is the so-called polar cap model. A pulsar is seen as a rotating neutron star with a dipole magnetic field similar in shape to the earth's but almost beyond comparison in strength. The earth's field at the surface is about half a gauss. Pulsar fields at the surface are calculated to be between 10 billion and 10 trillion (10^{10} to 10^{13}) gauss.

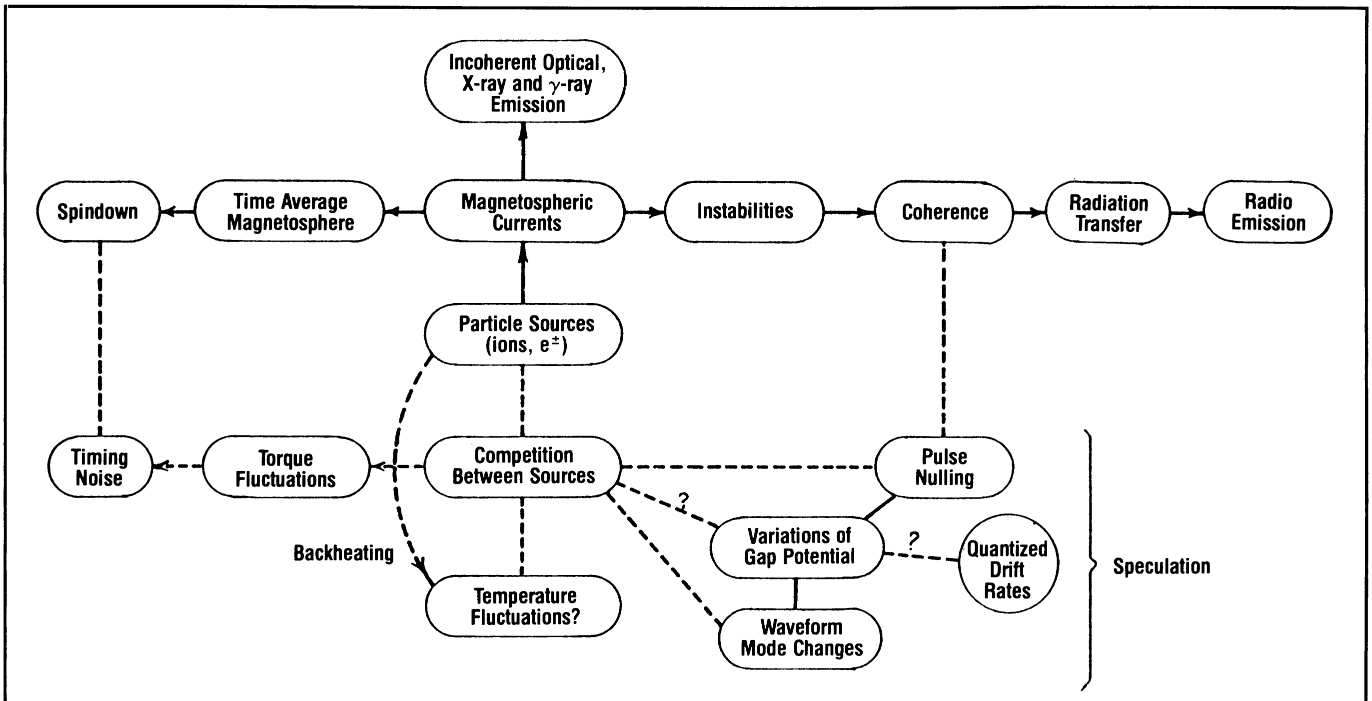
Near the surface at the neutron star's magnetic poles pairs of particles with opposite electric charges are pulled loose. These move out along the magnetic field lines providing electric currents and contributing to the buildup of a plasma or ionized gas above the poles. To get the observed pulsar radiation requires what is



PSR 0950+08: A sequence of pulse signals received at Arecibo Observatory in Puerto Rico.

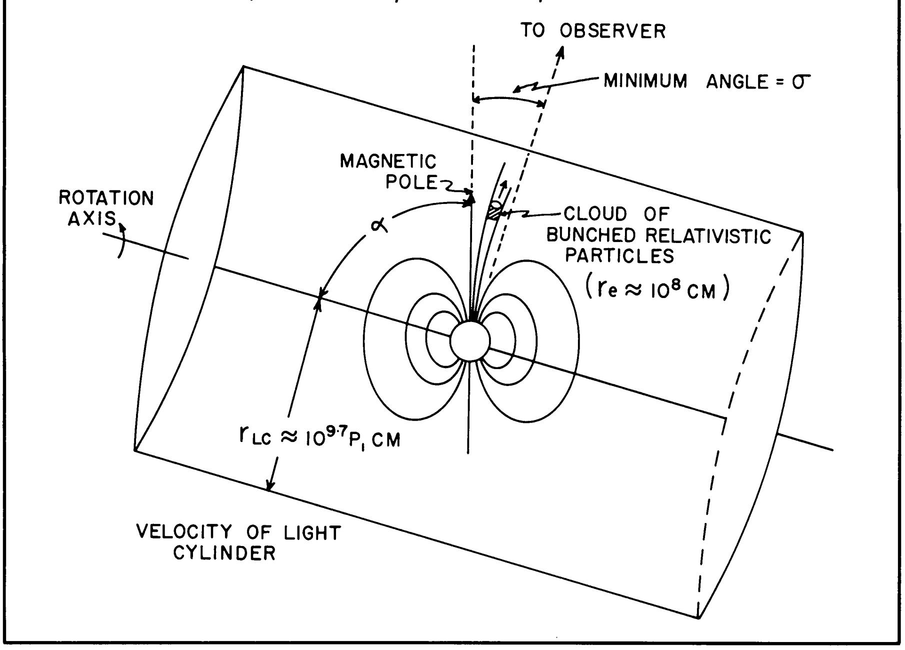
Researchers are closing the gap between observation and theory and are explaining in detail the phenomena known as pulsars

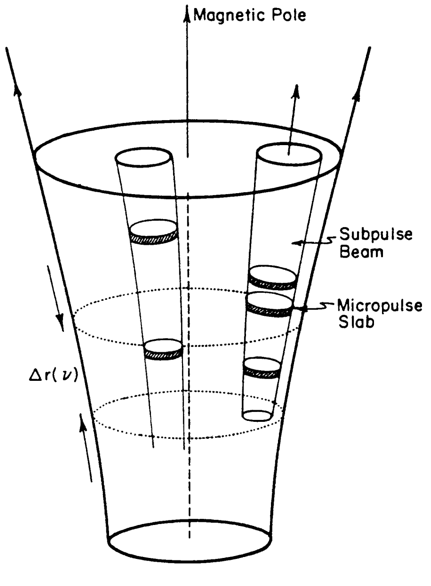
BY DIETRICK E. THOMSEN



Polar cap model: Solid lines connect orthodox features, dashed lines are speculation.

As the pulsating object rotates, the radiation beam sweeps the sky. If the beam cuts across the earth, radiotelescopes record a pulse.





A possible model for producing micropulses and subpulses.

Illustrations on these two pages: J. M. Cordes/Cornell University

called a two-stream instability, negative and positive particles streaming along two different open field lines (field lines that run out into space rather than looping around to the opposite pole). The currents and plasma would provide incoherent optical, X-ray and gamma ray emissions. The counter-streaming instabilities give the coherent radio emissions. The geometry of the field in which all these processes are taking place tends to beam all the radiation in the direction of the magnetic axis of the star. Like the earth's, the neutron star's magnetic axis is at some angle to its rotation axis. Thus the radiation beam gets carried around with the rotation and sweeps the sky. If it cuts across the earth on this sweep, our radio telescopes will receive a pulse each time it does.

Only one shape for this emission beam will explain the pulse shapes of many different pulsars, no two of which are exactly alike. Cordes showed "a rogues' gallery" of a few dozen. Many of the shapes are symmetrical about the midpoint of the pulse. There are single ones, double ones and triple ones, and the detailed relationships among the divisions of the multiple ones are quite varied.

The beam shape that fits so many is that of a hollow cone of radiation (a conical shell) with a pencil-shaped beam at its center. The cross section of this kind of shape is a ring with a circle at its center. As this pattern sweeps across the earth, radio telescopes will receive a pulse pattern with a shape that depends on how the earth cuts the beam pattern. If the earth grazes the ring, a single pulse results. The earth may cut the ring twice, giving a double. Or the earth may cut the ring and the central beam, yielding a triple pulse. The cut may go through the center of the pattern or off center and at any angle so the potential for fitting many different pulsars is apparent.

The polar cap model has less success explaining the subpulses and so-called micropulses. Micropulses are short, sharp spikes superimposed on the wider pattern of pulse and subpulse. Subpulses are an intermediate division of the main pulse.

There are times when the pulsar shuts off entirely. This may happen for anything from a few pulse periods to hundreds. Then it turns on again. Exactly why is unknown, but Cordes suggests that it has to do with the charged-particle production process at the surface of the neutron star. "I think there are competing sources of particles," Cordes says. "If you can shut off one, you can shut off the radio emission." But how to shut off one remains to be elucidated.

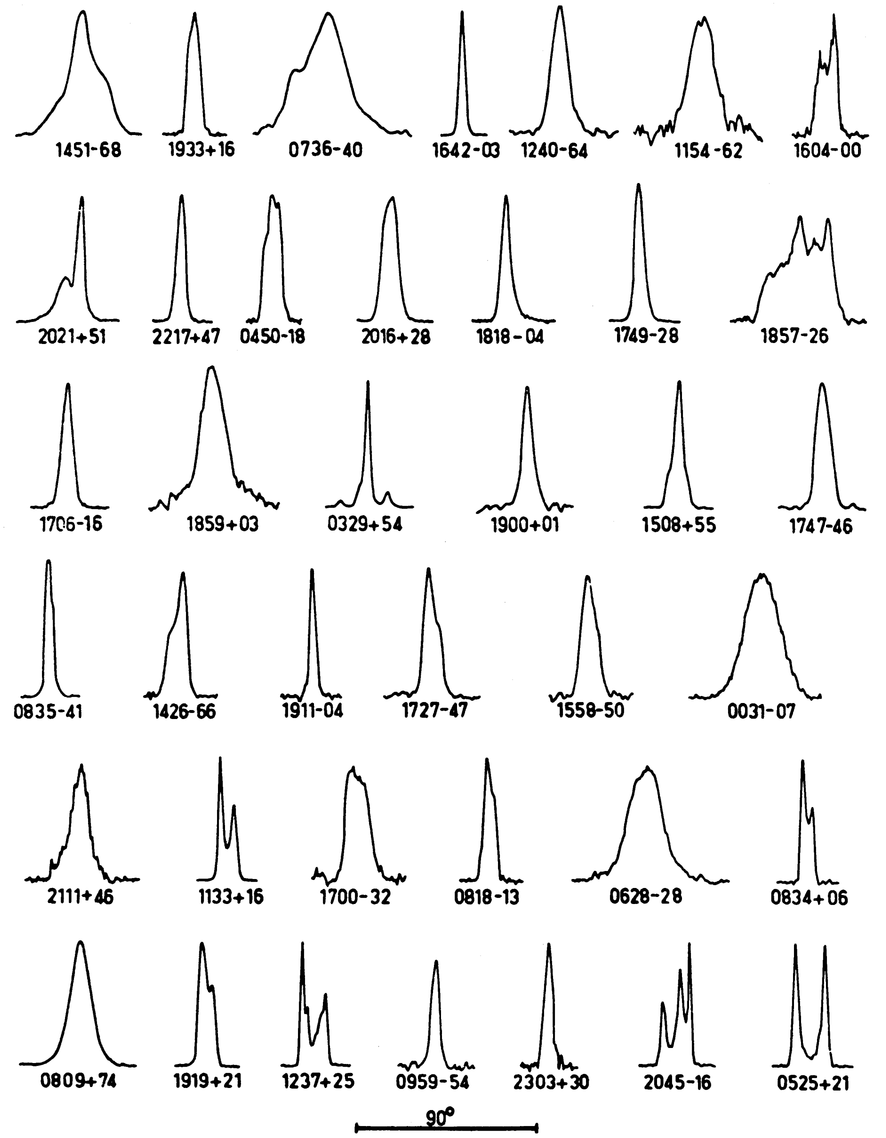
The model also fails to explain the observed circular polarization of the radio emission. The model as it stands will not yield circularly polarized radio waves, yet that is what is observed. Cordes concedes that this is a big problem. He suggests it may be solved by considering complicated radiative interrelations in the neutron star's magnetosphere.

In spite of these outstanding questions, Cordes says: "I see no reason to abandon this kind of model."

Besides the generation and beaming of the radiation, there is another major aspect of pulsar behavior that any successful model must explain. The slowing down of pulse rates over years — and even more curious — the bumpiness in the slowing.

The magnetosphere of the neutron star, which is where the radiative processes are going on, exerts a drag on the crust. (Since it is losing energy at a fast clip, it will be a drag, one way or another.) The crust of a neutron star is a material with nuclei far richer in neutrons than the nuclei of ordinary matter, but containing some other particles as well. It takes the form and behavior of a crystalline solid. The crust is about a kilometer thick. Inside it is another neutron-rich material that takes the form of a ball of fluid about 9 kilometers across. Under the conditions of pressure and density expected, this neutron star core may have the properties of a superfluid. There is observational evidence that it is a superfluid, which is very good for the theories.

A rogues' gallery of pulsars: No two are exactly alike.



J. H. Taylor and R. N. Manchester/Annual Review of Astronomy and Astrophysics

There are two kinds of variations in the slowing down of pulsars: glitches, which are sudden, sharp increases in rotation rate followed by renewed slowing down; and timing noise, which is random bumpiness in the rate as it slows down. Both can be related to the behavior of the superfluid.

As the crust tries to slow down, it drags on the superfluid. Under these circumstances lines of vortices appear in the fluid. Vortices form and line up parallel to the axis of rotation. The lines of vortices are distributed in a quantized pattern throughout the fluid. Each vortex line carries a quantum of the rotational motion (that is, angular momentum) of the superfluid.

To slow the superfluid down means to get rid of vortex lines. So the lines move away from the axis. But as they try to leave the fluid, they encounter the crust. According to one model that Cordes describes as "viable" a vortex line may become attached to nuclei in the crust. This causes a strain: The vortex line wants to speed up the crust. The crust is trying to slow down. The result will be a crack in the crust and a glitch in the star's rotation: a sudden speedup in order to slow down afterwards. Another suggestion depends on changes in the temperature at the core-crust interface. The efficiency of the coupling between core and crust depends on temperature. The fluid is always rotating a little faster than the crust, so if the temperature changes the right way, a larger amount of the difference can be delivered to the crust causing temporary spinups. Both glitches and timing noise can happen this way.

Part of the timing noise can also be explained by a mechanism in which the currents that start out from the magnetic polar caps can influence processes a long distance from the star (at the "light cylinder," the place where matter rotating with the star would move at a linear speed equal to that of light), and these processes in turn can have an influence back on the surface of the star that causes variations in torque, that is, up or down twists.

"There are a lot of problems here," Cordes concludes. Yet the picture of pulsars has developed a great deal since the first suggestion of neutron stars a dozen years ago. People may begin to believe there really are neutron stars out there. ☐