GLITCHES, TIMING NOISE, AND PULSAR THERMOMETRY

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It is shown that under certain assumptions the response of a neutron star to a perturbation in its temperature will be an increase in pulse repetition rate. Detailed models are presented which show behavior indistinguishable from the Vela pulsar period jumps. There appears to be no theoretical difficulty in arranging these events to recur every few years.

It is shown that starquakes and "hard superfluidity" are not capable of accounting for timing noise of the observed magnitude in the pulsars, but crust-breaking by vortex pinning and the heat-pulse model are.

INTRODUCTION

It has now been more than a decade since pulsar glitches were first discovered, and it is safe to say that even now there is no general agreement as to the origin of these rare and extraordinary events. The problem, of course, has always been the Vela Pulsar, which has undergone four glitches in ten years of magnitude $\Delta\nu/\nu$ = several parts per million. It has proved easy to construct models capable of explaining one such event per century or more, or many per decade of a far smaller magnitude. But the combination exhibited by the Vela Pulsar is difficult to understand.

For this reason, it has become fashionable to refer to the Vela events as "giant glitches" in order to distinguish them from the smaller "ordinary" events observed in the Crab Pulsar. By making this purely verbal distinction, it is implied that the Vela glitches must be somehow different in origin from the Crab's. Little point is served by this distinction, however. There is, in fact, *no observational difference whatsoever* between the glitches observed in Vela and the Crab Pulsar other than their size. We all know, of course, that advocates of this difference in terminology do so because starquake theory is capable of explaining the Crab's glitches but not Vela's. Rather than

W. Sieber and R. Wielebinski (eds.), Pulsars, 291–298.

allowing this to persuade us that two different processes are occurring in the two pulsars--processes that lead to events of the same observed signature--it seems more reasonable to search for a unified explanation for both.

A phenomenon related to glitches, but far more subtle in its observational interpretation, is that of pulsar timing noise. The process is sufficiently elusive that it initially gave rise to a number of mistakes in the literature, and a variety of theories were proposed in attempts to account for phenomena that had never existed in the first place. It was not until the pioneering work of Boynton et al. (1972) that its true nature was correctly identified: it is *noise in the pulsar clock*.

I am going to argue that with the help of one major simplifying assumption, all of these phenomena--glitches in the Crab and Vela pulsars as well as timing noise--can be understood as arising from the same underlying process. This process is *the response of a neutron star to a pulse of heat*. I am arguing that pulsar timing observations provide us with a kind of thermometer for neutron stars. To be more precise: timing observations tell us nothing about pulsar temperatures, but timing residuals do tell us something about fluctuations in these temperatures.

An important point to be noted is that the view I am presenting implies that glitches are not "pure" events. Rather, they are simply events that lie in a certain region of a spectrum. The spectrum is one of *time scale*. Fast events we notice and refer to as glitches. According to the heat-pulse model, however, slow glitches should also exist. These have precisely the same form as the fast ones, but take place over time scales of weeks or months rather than minutes. Because they are so slow, they have not yet been noticed. But they should be there.

THE MODEL

The model is described in full detail in Greenstein (1979). Its essentials are easy to summarize. It rests on two simple observations:

1. The superfluid interior of a neutron star rotates more rapidly than its crust, i.e., than the pulsar.

2. There is a frictional coupling between superfluid and crust which increases with the temperature.

Observation (1) is well known and follows from the simple two-component model of Baym et al. (1971). It implies, of course, that pulsars contain a good deal of "excess" angular momentum hidden beneath their surfaces. If a way could be found to transfer some of this excess up to the surface, we would have produced a glitch. Observation number (2) is equally well known, and its origin is easy to understand. Super-

https://doi.org/10.1017/S0074180900093049 Published online by Cambridge University Press

fluidity is a low-temperature phenomenon and becomes more pronounced the colder the system; if we raise the temperature, on the other hand, the superfluid will interact more strongly with its environment. It is with the help of observation number (2), of course, that we are going to transfer that excess superfluid angular momentum upward to the crust; we will do it by suddenly heating the star.

The consequence of a sudden pulse of heat is then a sudden increase in the frictional coupling between superfluid and crust. Of course, this does not discontinuously increase the rotation rate of the crust. The crust takes some time to spin up. Depending on the circumstances, the spin-up can be quite rapid, in which case we have produced a glitch. In other circumstances, the spin-up will be exceedingly slow; we get a slow glitch.

The above ideas should obtain in any region of the star in which the primary interaction between superfluid and charges is frictional in nature. It is known that in certain density regimes this is indeed the case. At other densities, however, vortex pinning becomes significant (Alpar 1977), and in these regimes, nothing that I have said here has any relevance. If this were all there was to it, we could simply apply the above analysis to that fraction of the star--certainly a dynamically significant fraction--in which pinning is unimportant. But it may not be permissible to do this. At the junction between the pinning and the frictional regimes a boundary layer of tangled vorticity will form. If this superfluid turbulence migrates into the frictional regime, its properties will be altered in ways that are both drastic and exceedingly difficult to calculate. At present, we do not even know whether it will so migrate. It may well not, in which case everything I say from here on should be quite accurate. In my view, this is the single most important unsolved problem in the whole area of superfluidity in neutron stars. In what follows, I will neglect it entirely.

GLITCHES

Greenstein (1979) describes a detailed model of the Vela Pulsar's glitches. A star is prepared with the period and period derivative of the Vela Pulsar and an initial internal temperature of 28 million degrees (entirely reasonable for a star of Vela's age). At t = 0, a 50% perturbation to the temperature is applied.

In response, the various regions of the superfluid spin down while the crust spins up. Within half an hour, the spin-up--the glitch--is complete. The spin-up is of magnitude $\Delta\nu/\nu \approx 4 \times 10^{-6}$, comparable to observed Vela glitches, and it is produced in times short compared to the time resolution of existing pulsar observations. Finally, after the glitch the pulsar angular velocity slowly decays back toward an ultimate offset. In every way, the behavior exhibited mimics the observed phenomenon of a glitch.

This, of course, is only half the problem. The real question is whether such events can be arranged to recur every few years. The thermal energy expended in heating the star by the required amount is of order $10^{40} - 10^{41}$ ergs. Can we arrange for such an energy to be released this often?

There appears, in fact, to be every reason to believe that we can. Indeed, it may be the case that pulsar temperatures, in contrast to the temperatures of every other class of object in the sky, are expected to fluctuate in time. This is because, first, the superfluidity, crystallization, etc., of neutron stars result in a greatly reduced specific heat; and, second, because neutron stars are subject to quite enormous decelerating torques. For example, the steady slowing down of the Vela Pulsar is accompanied by an energy loss of $\approx 10^{35}$ erg s^{-1}, all of which passes through the magnetosphere. At this rate, an energy sufficient to produce a glitch is radiated away in less than a day. There seems little difficulty in arranging for some small fraction of this flux--of order 10^{-4}--to be stored in the magnetosphere, to be returned every few years to the star in the pulsar equivalent of a lightning bolt. Alternatively, we note that in a wide variety of pulsar models there is a significant energy flux onto the stellar surface from the magnetosphere. If a fraction f of the spin-down luminosity is continually returned to the star in this way, then the star is heated to a surface temperature $T_e = 3/f^{1/4}$ million degrees; if the quantity f should fluctuate significantly, we might observe a glitch.

Finally, we note that a neutron starquake might produce the glitch--but for an unfamiliar reason. In a quake the net strain energy released as heat within the crust is of order

$$\Delta E = \frac{1}{2}\, I\Omega^2 \left(\frac{\Delta\Omega}{\Omega}\right) \text{ erg} .$$

This, even for a *small* quake of magnitude $\Delta\Omega/\Omega = 10^{-9}$, is sufficient to heat the star enough to produce a *large* glitch of magnitude $\Delta\Omega/\Omega = 10^{-6}$! We emphasize that there is no difficulty within starquake theory of arranging such events to recur every few years.

TIMING NOISE

As the result of an eight-year observing program by the University of Massachusetts pulsar observing group, we now have available for the first time a systematic survey of timing noise in the pulsars. The results of this survey are given by Cordes and Helfand (1980) and the references contained therein. For my present purposes, the most significant results are the quantitative measurements of the noise strengths, e.g., $S \equiv R(\Delta\nu)^2$, for frequency-noise pulsars, where R is the rate of frequency steps and $\Delta\nu$ their magnitude. Cordes and Greenstein (1980, hereinafter referred to as CG) have undertaken a detailed study of the consequences of these observations for a variety of models that have been proposed to account for pulsar timing noise. It proves to be very difficult to obtain noise strengths of the observed magnitude within many of them:

1. Starquakes

Historically, this was the first model proposed to account for the observed phenomenon. We imagine that a continual series of microscopic quakes, of magnitude $\Delta\nu$, are occurring at a rate R events/sec. Now, starquake theory (Baym and Pines 1971) provides a relation between the magnitude $\Delta\nu$ of a quake and the time $\Delta t \equiv 1/R$ between quakes:

$$\Delta t = \omega^2 \Delta\nu / \nu^2 \dot{\nu} ,$$

where ω^2 is a structure-sensitive parameter that can be calculated from an assumed equation of state. Thus, the predicted noise strength

$$S = (\nu^2 \dot{\nu} / \omega^2) \Delta\nu$$

depends on the magnitude of the microquakes and can be made as large as we like by suitably adjusting $\Delta\nu$. However, the observations provide us with an upper limit on $\Delta\nu$. The question is, then, can S be made large enough to meet the observations without violating this limit?

The answer is no for all pulsars except the Crab. Starquake theory fails to account for timing noise in long-period pulsars for the same reason that it fails to account for glitches in Vela: it cannot be made to yield events as large and as frequent as observed. CG were able to establish this result quite rigorously for crustquakes and with a high degree of force for corequakes. Finally, Pines and Shaham (1972) have proposed a model in which microquakes are produced by a component of the torque perpendicular to the spin axis; so long as this component does not exceed the parallel component by many orders of magnitude, the argument should apply to their model as well.

2. "Hard superfluidity"

Anderson and Itoh (1975) have noted that vortex lines slowly migrate outward as a neutron star's rotation is slowed, but that they may hang up at pinning sites from time to time. The resulting erratic vortex motion will produce corresponding fluctuations in the pulsar angular velocity.

We are able to place important constraints on this picture in the following oversimplified way (for a more complete analysis, see CG): If one line hangs up at a pinning site for a while and then suddenly jumps outward by a distance d, the superfluid suddenly slows, dropping its angular momentum by $\Delta L/L \approx d^2/NR_*^2$, where R_* is the stellar radius and N the total number of vortex lines in the star. The corresponding jump in pulsar angular velocity is $(\Delta\nu/\nu) = (I_s/I_c)(\Delta L/L)$. What is an

https://doi.org/10.1017/S0074180900093049 Published online by Cambridge University Press

appropriate choice for d? The steady migration velocity of a line is $v \approx R_*/t_s$, where t_s is the spin-down age of the pulsar. If the line had remained pinned a time Δt, then $d \approx v\Delta t$ seems an appropriate guess. Finally, if τ is the time between successive pinnings of a line, then $R = N/\tau$ is the rate of events. Putting all this together, we obtain a noise strength

$$S = \frac{N}{\tau}\,[\nu(I_s/I_c)(\Delta t/t_s)^2(1/N)]^2 \; . \qquad (1)$$

We have two constraints: First, by definition, $\Delta t < \tau$; secondly, by observation, the rate N/τ exceeds one event per year. We then obtain an upper limit on S: *this limit is some ten orders of magnitude too small to account for timing noise.*

The structure of equation (1) yields an important insight into why this version of the Anderson-Itoh model fails. The estimated strength is inversely proportional to N, the total number of vortex lines in the star. Because N is so very large, the effects of the erratic motion of a single line are washed out. Thus, *if the model is to be maintained, it must be large bundles, containing* $\gtrsim 10^4$ *lines, rather than the individual lines themselves that pin and unpin as units.*

3. Crustbreaking by vortex pinning

Ruderman (1976) has proposed a method for accomplishing this. He notes that when vortex lines pin, they are pinned to something rotating at a different rate than the background superfluid. Under these circumstances, a strong shearing Magnus force is transferred to the crust. He argues that in certain density regimes, the pinning force is sufficiently strong that the lines will never unpin; rather the crust will ultimately fracture, allowing them all to jump outward at once.

It is easy to show that under these assumptions the resulting noise strength greatly *exceeds* what is observed. *The problem now is not why timing noise is so big; it is why it is so small.* It remains to be seen whether this problem can be successfully addressed.

4. Response to a heat pulse

It will come as no surprise to the reader to learn that the heat-pulse model I am advocating is also capable of meeting the observations. Furthermore, the model does not appear to be troubled by an embarrassment of riches.

In the first case, as shown by CG, *the heat-pulse model is capable of yielding noise strengths of the observed magnitude.* Furthermore, following CG, a number of limits can be placed upon various parameters in the model. First, for the particular equation of state assumed by CG, the internal temperatures of those pulsars exhibiting frequency noise are constrained to lie in the range 2-4 million degrees, comfortably within theoretical expectations. Depending on their masses, this translates into surface temperatures between 3×10^4 K and 4×10^5 K. The upper portion of this range lies close to the best presently available limits on temperatures for these pulsars, and the observational situation very well may improve. Second, the model finds it far easier to accommodate a noise process consisting of relatively infrequent large events--one per month, let us say--as opposed to more frequent small ones. Again, this, too, is capable of observational confirmation. Finally, the model is capable of accounting for the distinction between frequency noise and phase noise, although it appears quite incapable of yielding slowing-down noise.

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DISCUSSION

ITOH: What sort of opacity did you use in order to obtain the surface-temperature range in which your theory is valid?

GREENSTEIN: A very crude opacity. I would like to see more accurate computations.

CHENG: For your Vela macroglitch model, a thermal energy input of a few times 10^{40} erg is required to trigger the event. If a comparable energy is radiated from the surface of the star, a time-averaged luminosity of $\gtrsim 10^{33}$ erg s^{-1} is implied by the observed glitch occurrence rate. Is this not already near to or inconsistent with the recent Einstein Observatory results?

GREENSTEIN: HEAO-B observations have set an upper limit of $\approx 10^{33}$ erg s^{-1} on the unpulsed x-radiation from the Vela pulsar. This is close to, but not in strong contradiction with, a requirement of 10^{40} erg thermal energy release associated with each glitch.

I should also add that 10^{40} erg are required to produce a Vela-sized glitch only if they are uniformly spread over a large fraction of the entire volume of the star. But if the energy release is local — as it is in a quake — thermal conductivities are such that the excess heating will remain confined to a small region. Thus my estimate of 10^{40} erg can be reduced somewhat.

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LAMB: Apart from starquakes you mentioned only heating mechanisms (accretion, electrical currents, and magnetospheric instabilities) which heat the stellar surface rather than the interior. In general, all but a tiny fraction of such heat will be radiated away. Furthermore, the time scale for surface heat to diffuse into the inner crust or core is probably not negligible in comparison to the time scale of changes in the relative angular velocities of crust and superfluid, or the observed time scales of glitches. Processes, such as starquakes, which heat the interior directly would seem to be much more promising.

GREENSTEIN: It may indeed be true that any heat pulse applied to the surface of a neutron star is extremely ineffective in heating the interior. But the fact remains that the spin-down luminosity of the star $I\Omega\dot{\Omega}$ is enormous on the scale of energies required. The primary thrust of my remarks was to indicate that the heat pulses which this model needs to account for the Vela pulsar glitches are easy to obtain.