Astronomical clocks

Probing the early Universe with the millisecond pulsar

from Bernard Carr

COULD the millisecond pulsar known as PSR1937+21 provide information about processes that occurred within the first millisecond of the Big Bang? That is one of the intriguing questions raised by the results reported by M.M. Davis, J.H. Taylor, J.M. Weisberg and D.C. Backer on page 547 of this issue.

The millisecond pulsar was discovered in 1982 and immediately gained prominence as the pulsar with the shortest known period; according to theory, its signal must be produced by a neutron star rotating at a thousand times a second. What promises to make PSR1937+21 such a useful cosmological probe, however, is that its rotation rate remains remarkably constant: apart from a steady and well-understood increase due to its energy emission, the rate has remained stable to one part in 10^{13} over two years. The pulsar thus provides an extraordinarily accurate clock, of relevance to cosmology in that many processes in the early Universe are expected to produce a background of gravitational waves, which should induce a tiny jitter in the clock's regularity.

To demonstrate the stability of the millisecond pulsar required considerable effort. The radio signal of the pulsar was timed initially with a rubidium clock at Arecibo Observatory but a multitude of corrections had to be applied before its regularity could be inferred. The rubidium measurements had first to be checked for any drifts relative to the master clock in Washington and then corrections had to be made for such effects as the relativistic delay induced by the gravitational field of the Sun, the changing Doppler shift associated with the Earth's motion through the Solar System and the dispersion produced by interplanetary and interstellar plasma. Most of these effects can be estimated with high accuracy and, after they were allowed for and a best fit made for the location, period and spin-down rate of the pulsar, the residual noise is only about one μ s over the observation period of two years. This is comparable with the accuracy of the best man-made atomic clocks. The residual noise may in part derive from the fact that the corrections mentioned above are imperfect. If so, improved estimates of these corrections could eventually reduce the residual noise to only 0.1 μ s. For the present discussion, the most interesting source of noise would be gravitational waves. If the waves have a dimensionless amplitude h and a period P (assumed to be less than the light-travel time to the pulsar), then they will change the arrival time of the pulses by an amount hP , an effect first

pointed out by S. Detweiler (*Astrophys. J.* **234**, 1100; 1979). For a continuous background of waves, this will induce a residual of no more than $h\tau$ over a time τ , because the pulsar is most sensitive to waves with $P > \tau$. (The effects of waves with $P < \tau$ would be largely absorbed into the fit to P and its derivative.) If the pulsar clock has an accuracy of Δt , it can be used to look for waves with period τ and amplitude $h = \Delta t/\tau$.

For PSR1937+21, the limiting amplitude is presently down to 10^{-14} , which means that one may already exclude a density of gravitational waves comparable with that in the microwave background ($\Omega_r \approx 10^{-4}$ when expressed in units of critical density). However, the limiting density scales as $(\Delta t)^2 \tau^{-4}$ and so the sensitivity of the millisecond pulsar as a gravitational wave detector is likely to improve dramatically with time. For example, if the timing residual can be reduced to 0.1 μ s, and if this stability can be maintained over 10 yr, the pulsar could eventually search for a background of waves with density as low as $10^{-4} \Omega_r$.

The sensitivity of the millisecond pulsar is optimized for waves whose period is comparable with the observation time (a few years). Unfortunately, the most prolific sources of gravitational waves at the present epoch (supernovae and black holes) are likely to produce waves with periods much shorter than this. The one exception might be a population of binary black holes; these would produce radiation through quadrupole losses and could, in principle, be detectable if they were sufficiently numerous (J.R. Bond and B.J. Carr, *Mon. Not. R. astr. Soc.* **207**, 585; 1984). However, the most likely source of gravitational radiation in the required waveband would be processes that occurred in the early Universe.

This can be understood as follows. Cosmic processes which occurred at a time t after the Big Bang tend to produce radiation with a wavelength of the order of the horizon size at that time (ct); when one allows for redshift effects, this corresponds to a present period of about $(t_0 t)^{1/2} \approx (t/10^{-4} \text{ s})^{1/2} \text{ yr}$, where $t_0 \approx 10^{10} \text{ yr}$ is the age of the present-day Universe. Thus, the millisecond pulsar can be used to look for waves generated at around 10^{-4} s , providing their amplitude is large enough. It turns out that the condition on the amplitude can be satisfied only if the waves are generated later than a time Δt after the Big Bang. The timing residual of PSR1937+21 thus directly determines how far back we can probe the history of the Universe.

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The period around 10^{-4} s is rather significant as it corresponds to the time of the cosmological phase transition at which free quarks transform into nucleons. Recently, E. Witten (*Phys. Rev. D* **30**, 272; 1984) has suggested a rather interesting way in which this phase transition could have generated gravitational waves. If the transition is first order and proceeds by the formation of bubbles which expand explosively, one would expect a gravitational wave background to be generated when the bubbles collide. It is not clear whether the amplitude of the waves would be large enough to be detected by the millisecond pulsar, but it is conceivable. Another consequence of this scenario is that the fraction of the Universe outside the bubbles would be compressed into invisible quark 'nuggets', which might be candidates for the dark matter in galactic halos.

Various other effects in the early Universe could produce a gravitational wave background. For example, if the Universe undergoes an inflationary phase (a period of exponential expansion) at some epoch, characterized by a Hubble rate H , then one expects quantum effects to generate waves with density $(H/M_p)^2 \Omega_r$ over a wide period range; here M_p is the Planck mass. This effect was first pointed out by A.A. Starobinsky (*JETP Lett.* **30**, 682; 1979). Such an inflationary stage may occur at around 10^{-35} s after the Big Bang, according to the Grand Unified theories, as a result of the Universe getting trapped in a false vacuum state; it may also occur because of quantum gravity effects. In this situation, the waves detectable by the millisecond pulsar would not be generated at 10^{-4} s , but they would fall within the horizon at 10^{-4} s .

Another possibility is that the Universe could undergo spontaneous symmetry breaking at some epoch, resulting in the formation of cosmic strings. These strings can be thought of as topological defects which are trapped in the symmetrical state and, if some of them form closed loops, they should generate gravitational waves through oscillations. The spectrum of the waves expected is rather complicated (C.J. Hogan and M.J. Rees, *Nature* **311**, 109; 1984) but in the period range relevant to the millisecond pulsar it would be flat with a density of the order of $(T/M_p)\Omega_r$, where T is the temperature of the symmetry breaking. It has been proposed that sufficiently large loops could serve as seeds for galaxy formation (A. Vilenkin, *Phys. Rev. D* **24**, 2082; 1982); this suggestion is already close to being tested by using the millisecond pulsar to look for the associated gravity waves. Although there are other ways of detecting gravitational waves, such as laser interferometry, none is sensitive to waves with a period of a year. Therefore, given time, PSR1937+21 could serve as a unique cosmological probe. □

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