A. D. Kuz'min. *The pulsar time scale.* In 1979 Soviet scientists proposed a new time scale based on the periodicity of radio-frequency radiation pulses from pulsars.[1,2] By virtue of its astronomical nature this scale would be long-lived, reproducible, identical for all observers, and would have unique null points.

The primary standard of this scale is provided by the pulsar. The scale is defined as the continuous sequence of time intervals between pulsar radiowave pulses

$$t_N = t_0 + P_0 N + \frac{1}{2} P_0 \dot{P}_0 N^2, \qquad (1)$$

where P_0 and $\dot{P}_0$ are the period and its derivative at the initial moment in time and N is the current pulse number. Parameters P_0 and $\dot{P}_0$ are stable characteristics of a given pulsar. Consequently, if they are measured once, relation (1) may be employed to predict the future pulse arrival times.

Since the Earth rotates about its axis and revolves around the Sun the distance of the time scale apparatus from the pulsar changes and, consequently, so does the pulse propagation time. In order to exclude this effect the time is referred to a fixed point in the inertial coordinate system—the barycenter of the Solar system—according to the relation

$$t_б = t_н + \frac{\mathbf{r}_\oplus \mathbf{n}}{c} - \Delta t_p, \qquad (2)$$

where t_n is the observed pulse arrival time, $\mathbf{r}_\oplus$ is the vector connecting the observer with the barycenter, $\mathbf{n}$ is the barycenter-pulsar unit vector, and Δt_{rel} is the relativistic correction for the timekeeping of an earth-based clock in the variable gravitational field experienced by the earth in its orbital motion.

A sequence of measurements according to this program has been carried out at the Radioastronomical Station of the FIAN (Pushchino, Moscow region) since 1979. The most stable pulsars known at the time, PSR 0834 + 06 and 1919 + 21, were used. The results are illustrated in Fig. 1 in terms of the Allen dispersion:

$$\sigma(\tau) = \frac{1}{2} \langle [(R(t+\tau) - 2R(t) + R(t-\tau)) \tau^{-1}]^2 \rangle, \qquad (3)$$

where τ is the measurement interval, $R(t)$ is the deviation of the pulse arrival time from the expected, as defined by expression (1). The Allen dispersion measurements on atomic time standards are also plotted in Fig. 1.

For an ideal clock the deviations R would be a random variable, independent of the measurement interval τ, and the dispersion $\sigma(\tau)$ would fall linearly with τ. In Fig. 1 we find that $\sigma(\tau)$ does indeed fall with τ. But for atomic standards this trend persists for short measurement intervals only (for the cesium standard $\tau \approx 10$ days). At longer intervals $\sigma(\tau)$ ceases falling and even begins to increase, indicating unpredictable drifts that hamper high precision.

In the case of pulsars, $\sigma(\tau)$ continues to fall over the

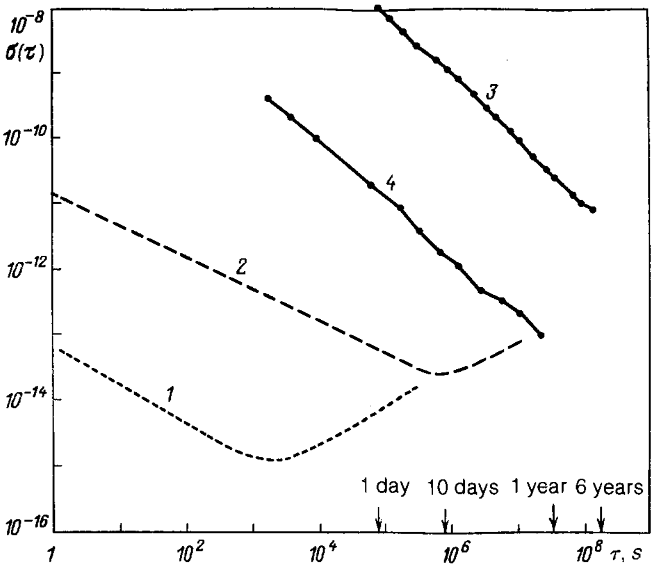

FIG. 1. Allen dispersion $\sigma(\tau)$ as a function of the measurement interval: 1—hydrogen standard, 2—cesium standard, 3—pulsars PSR 0834 + 06 and 1919 + 21, 4—pulsar PSR 1937 + 21.

entire range of measurement intervals $\tau = 6$ years, testifying to the high predictability of the pulsar time scale over long intervals. However, because of large deviations R the values of $\sigma(\tau)$ for pulsars are much larger than for atomic standards.

The magnitude of R is limited by the measurement error of the pulse arrival times. This error is proportional to the pulse duration, which is proportional to the period of the pulsar. The pulsar PSR 1937 + 21 was discovered in 1982:[3] its period of 1.5 ms is about one thousand times shorter than the periods of PSR 0834 + 06 and 1919 + 21. The pulse duration and error in the measured pulse arrival time ($\delta t = 1$ μs) are correspondingly smaller. The Allen dispersion for this pulsar over an interval of about six months reaches 10^{-13} (see Fig. 1) and is comparable to the best atomic standards.[4,5] The absence of unpredictable deviations indicates that over longer intervals the pulsars could serve as the most predictable clocks.

Solving equation (2) with respect to $\mathbf{r}_{\oplus}\cdot\mathbf{n}$ makes it possible to determine the location of the Solar system barycenter and planetary ephemeris times, as well as the motion of the barycentric coordinate system in the Galaxy. Distances to pulsars can also be measured in this way.

The pulsar time is quite a sensitive detector of the background gravitational waves (GW) which alter the space-time metric. This leads to changes in the pulse arrival time $\Delta t = hT$, and by measuring this shift we can calculate the GW energy density

$$\rho_g = \frac{\pi}{2G}\Delta t^2 \cdot T^{-4}, \tag{4}$$

where T is the GW period. Since the measurements reported by Davies and co-workers[4,5] revealed no deviations in the pulse arrival times from the predicted values, these researchers were able to evaluate the upper limit on ρ_g (in terms of $\Omega_g = \rho_g/\rho_c$, where ρ_c is the critical density of the closed Universe). For GW frequencies[1-3] of 0.8 and 0.23 years^{-1} they calculated upper limits on Ω_g of $<5\times10^{-4}$ and $<3.5\cdot10^{-7}$ respectively.

The results of these estimates, in terms of the ratio of the GW energy density to the critical density of the closed Universe $\rho_c = 2\cdot10^{-29}$ g·cm^{-3} are plotted in Fig. 2 together with values obtained by other methods.

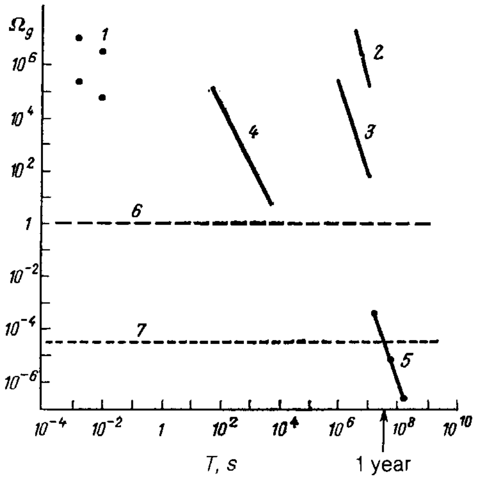

FIG. 2. Upper limits on estimates of the energy density of gravitational waves (with respect to the critical density of the closed Universe $\rho_s = 2\cdot10^{-29}$ g·cm^{-3}): 1—Weber oscillators, 2—4—orbit evolution of Mercury, Mars, and the "Voyager" probe, 5—pulsar PSR 1937 + 21, 6—$\rho_s = 2\cdot10^{-29}$ g·cm^{-3}, 7—energy density of the radiowave background at 2.7 K.

Thus we find that the pulsar time time scale enables us to construct the most reliable clock over long intervals, as well as contributing to the solution of a number of fundamental problems in astrometry and to the search for gravitational waves. The materials of this report have been published in Refs. 2 and 6.

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