PULSARS. SURVEY OF OBSERVATIONAL DATA

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The main observational data on pulsars are briefly reviewed. The ages of pulsars are discussed in connection with their evolution. Two evolutionarily independent types of pulsars are ~~introduced~~ introduced.

1. Introduction. No astrophysical phenomenon has been the subject of such intense investigation during the last decade as pulsars. What makes the pulsating radio sources unique is the pulsed nature of their emission with exceptionally short — of the order of a second and less — pulsation period, this having an extraordinarily high stability that sometimes reaches 10^{-10}. These astrophysically unexpected properties of the emission of pulsars stimulated systematic observations aimed at the comprehensive study of their characteristics and intrigued the theoreticians by the possibility of finally encountering in reality the hypothetical neutron stars.

The importance of investigating pulsars became clear immediately after their discovery. And although much remains obscure in the physics of the pulsar phenomenon, some definite ideas about these objects were formed already in the first years after their discovery. It is true that these ideas were based on the comparatively small number of pulsars known at that time, and today their number has grown considerably; nevertheless, these ideas have not undergone significant change but have rather received statistically more significant confirmation. The ideas are presented in the original surveys of Hewish [1], ter Haar [2], Taylor and Manchester [3], and others [4-8].

Up to the present date, more than 500 scientific papers and communications on pulsars have been published. They are devoted to searches for pulsars and techniques of their observation and study of the characteristics of the radiation and its spectral and polarization properties. Being objects in our Galaxy, the pulsars provide excellent possibilities for studying the structure and properties of the interstellar medium. Studies aimed at constructing a theory of pulsars play a serious heuristic part in our understanding of their nature.

In the first two parts of the present review, we present the main observational data — both the individual characteristics of the pulsars and properties they possess as members of our Galaxy. We shall not discuss the mechanism of radiation or models and theories of pulsars. In the third part, we consider the ages of pulsars and, in particular, the initial periods with which pulsars are "born". This analysis helps to clarify the estimates of the true ages of pulsars, which are important for an understanding of their evolution.

2. Discovery of Pulsars. The first pulsars (1919 + 21 and 0834 + 06, 0950 + 08, 1133 + 16) were discovered in 1967 at Cambridge by J. Bell and A. Hewish* in systematic observations of interplanetary scintillation [9-11]. The largest radioastronomical observatories in the world then joined in the search for pulsars. In the course of the year, six further pulsars were discovered; by 1970, 50 had been discovered, and by 1975 the total was about 150. A survey of the most complete and accurate data on these pulsars and references to the corresponding sources are given in [12].

At the end of 1978, Taylor, Manchester, et al., [18] published a list of 155 new pulsars, and soon after there appeared the communication [19] with the discovery of a further 17 new pulsars. Thus, the total number of currently known pulsars is 321. The overwhelming majority of them have been discovered in sky surveys at the observatories at

*In 1974, the Nobel Prize was awarded to M. Ryle for aperture synthesis and A. Hewish for the discovery of pulsars.

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Molonglo (Australia) [13, 18, 19], Jodrell Bank [14, 15], and Arecibo (USA) [16, 17]. These surveys cover the entire southern sky and a considerable fraction of the northern half of the sky ($b < 20^{\circ}$).

As is reported in [18], among 224 detected pulsars 69 were already known. If the process of pulsar discovery is assumed to be random (the properties of the pulsar radiation allow a nonzero probability of its escaping detection),* then from the data on the number of previously known pulsars $n_1 \sim 150$, the newly detected $n_2 = 224$, and the twice detected $n_{12} = 69$, one can estimate the total number N of pulsars that could be detected under present-day conditions of observation (technology and surveyed region of the sky) in accordance with the simple formula

$$N = n_1 n_2 / n_{12} \approx 490. \tag{1}$$

According to [19], $n_1 \approx 300$, $n_2 = 43$, $n_{12} = 26$, and we obtain the same estimate $N \approx 500$. Therefore, in coming years we can expect the discovery of approximately 150-200 new pulsars.

I. Individual Characteristics of Pulsars

3. The Pulses and their Stability. The emission of pulsars is pulsed with peaks repeated regularly at equal intervals of time, which are called the pulsar period. In some pulsars, a weaker intermediate pulse is observed between two main pulses, not infrequently in the middle.

The fluxes in the pulses exceed the flux in the period between them by tens and occasionally hundreds of times, so that the mean flux over a prolonged period of time is usually of the order of the background flux. For example, in the pulsar 1919 + 21, which was the first one discovered [9], the most powerful pulses reach $2 \cdot 10^{-25}$ $W \cdot m^{-2} \cdot Hz^{-1}$, and the mean flux density is 10^{-26} $W \cdot m^{-2} \cdot Hz^{-1}$. This means that pulsars are extremely weak sources — their mean fluxes are below the sensitivity of the receivers used for large-scale sky surveys [10].

The pulsar periods have an exceptionally high stability. For example, for 1919 + 21 the period has been measured with an accuracy to a few units in the twelfth place: 1.33730119227 sec. Usually, the stability of the pulsar periods is of the order 10^{-6}-10^{-11}. This high accuracy of signal repetition indicates a global nature of the emission of the pulsar as a whole [10].

4. Width of the Pulse and the Size of Pulsars. In almost all pulsars, the pulse duration is a few percent of the total period, so that a fairly clear direct correlation can be established between the pulse width and the period. The characteristic pulse half-width is between a few and several tens of milliseconds. A very important conclusion concerning the sizes of pulsars can be drawn from the width of the pulse. Given that the pulsar emission has a global nature, radiation must be observed from different parts of the source in a time interval W equal to the pulse width, i.e., in this period light must succeed in traversing a distance r of the order of the pulsar diameter. It follows that

$$r \lesssim W \cdot c, \tag{2}$$

where c does not exceed the velocity of light in vacuum. Such (upper) bounds lead to characteristic pulsar dimensions from hundreds to a few thousand kilometers. For the pulsar 1919 + 21, W = 25 msec and $r \approx 5000$ km.

5. Fluctuations of the Amplitude. The amplitudes of the pulses undergo strong variations during the course of days, hours, minutes, and even from pulse to pulse. For example, for 1919 + 21 the pulses are observed for one or two minutes, after which they "die out" for two or three minutes. In the case of the pulsar 0943 + 10, which was discovered at Pushchino [22, 23] these gaps are so long that pulses were observed only a few times in the course of a month. Usually, the pulses cease abruptly, for several periods, and then reappear as abruptly. In some pulsars, prolonged variations in intensity — by an order of magnitude over a period of months — are observed [24].

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*According to the same communication [18], 30 known pulsars in the surveyed region of the sky were not detected.

On the whole, the amplitude fluctuations are irregular, but in a number of pulsars strong periodic variations in a sequence of individual pulses are observed. The period of such variations in the pulsar 0834 + 06 is equal to twice its basic period. The rapid fluctuations of the amplitude are largely due to the nature of the emission itself rather than, say, scintillation due to inhomogeneities of the interstellar medium.

6. Mean Profile of the Pulses. Despite the strong fluctuations in the intensity of successive pulses, for each pulsar there is a definite stable profile of the mean pulse, which can be obtained by superimposing a large number of periods (by integrating over a few minutes). The mean, or integral, profile of the pulse is very stable throughout the entire time of observation of a given pulsar. However, it is completely different for different pulsars, serving as a "signature" of the pulsar.

The integral profile has the form of an individual, or, frequently, two clearly expressed peaks, and in rare cases between three and five peaks. Naturally, the width of the integral profile is several times greater than the width of individual pulses, corresponding to the number of component peaks. The distance between these components depends weakly on the frequency, a greater separation between the components usually corresponding to lower frequencies.

Within the integral profile, the individual pulses are distributed randomly, so that the profile of the mean pulse reflects to a certain extent the distribution of the probability for the occurrence of an individual pulse at a particular phase of the profile. However, there exists a class of pulsars with drifting subpulses; in these, individual pulses follow one another regularly within the integral profile, being displaced steadily from the trailing edge to the leading edge in their sequence.

Huguenin, Taylor, and Manchester classify pulsars on the basis of the integral profile into the following types: S with simple profile, C with complicated profile, and D with drifting subpulses [25-27], and they note correlations between a number of properties of pulsars according to their types. In particular, the S pulsars have short periods and the C pulsars have very strong polarization.

7. Secular Variation of the Periods. The periods of the majority of pulsars lie in the interval from 0.1 to 2 sec. They are less than 0.1 sec for only three pulsars, and greater than 2 sec for only six. Measurements over a considerable period of time make it possible to find the rates of change $\dot{P}$ of the periods with time. As a rule, the measured values of $\dot{P}$ are positive, i.e., the pulsar periods increase. Typical rates of change are $1\text{-}10 \cdot 10^{-15}$ sec/sec. In some pulsars, they exceed the values 50-100, and in the pulsar 0531 + 21, which has the shortest period, the value is highest: $423 \cdot 10^{-15}$ sec/sec. The only pulsar with a shortening period is 1813 — 26 ($\dot{P} = -0.3 \pm 0.3$).

Besides the regular increase in the period, in some pulsars irregular deviations from linear increase are observed. Of particular interest are the sudden abrupt decreases — glitches — in the period. Such glitches have been observed several times in the Vela pulsar and in the pulsar in the Crab Nebula. The strongest glitches have reached 100-200 nsec, and this over time intervals that certainly do not exceed weeks. The glitches are followed by a slow relaxation of the rate of increase of the period to its previous value [28-33].

8. Spectra. It is usually difficult to study the spectra of the pulsar emission because of the strong and rapid variations in intensity. One therefore usually determines the spectrum of the integral pulse, which is fairly stable over a period of many years (see, for example, [34]).

Pulsars are observed in the radio range from tens of MHz to tens of GHz. The pulsar spectra have a decreasing profile with abrupt dip at high frequencies. A typical profile of the spectrum is

$$S \sim \omega^{\alpha}, \tag{3}$$

where the spectral index α for different pulsars takes values from —1 to —3. In some pulsars, a low-frequency limit of the spectrum is observed. The individual components of a pulse usually have different spectral indices.

The radio luminosities of the pulars lie in the interval $10^{26}\text{-}10^{29}$ erg/sec. They have been calculated [12] in the range of frequencies $\Delta\omega \approx 400$ MHz under the assumption that the pulsed radiation is concentrated within a cone (in agreement with the "pencil" model of a pulsar) with opening angle determined by the pulse width $2\pi W/P$. For isotropic emission, the luminosities will be about three orders of magnitude higher.

9. Polarization. The pulsar radiation is usually very strongly polarized, linear polarization predominating over circular polarization. Polarization parameters change systematically within an individual pulse. For example, the position angle increases monotonically (or decreases), independently of the frequency and most strongly near the middle of the pulse. The sign of circular polarization also changes there.

Despite the strong changes in the polarization parameters from pulse to pulse, a fairly high degree of polarization remains in the integral profile. In pulsars with drifting subpulses, the position angle is closely related to the phase of the subpulse.

II. Pulsars and the Galaxy

10. Scintillation. Pulsars were discovered in observations of interplanetary scintillation — the diffraction of radio waves on clouds of plasma (charged partcles) of the solar wind. The scintillations are most noticeable at relatively long wavelengths (~4 m) and have a characteristic time of the order of a second. Interplanetary scintillation makes it possible to obtain very accurate data on the angular diameters of radio sources, expecially ones of small angular diameter (for example, pulsars). Since interplanetary scintillation is slight at night (it was at night that the signals from the pulsar 1919 + 21 were observed), its influence on the intensity variations of the pulsar radiation can be eliminated.

Scintillation can also arise through inhomogeneities of the interstellar medium, giving rise to strong variations in the flux and thus affecting both the spectral and time characteristics of pulsars. The characteristic dimensions of the inhomogeneities of the interstellar medium are of order 10^6 km and the scintillation arises with a relative change in the line of sight to the pulsar. The reciprocal of this rate of change determines the characteristic scintillation time, which varies from a few minutes to hours and even days (but not seconds or months), with a mean value of about 20 min. The observed correlation time of the scintillations corresponds to relative velocities of the pulsar motion of more than 100 km/sec.

The scintillations lead to an observable broadening of the pulse profile, which takes the form of a spreading of the trailing edge of the pulse at low frequencies, especially for pulsars with large values of the dispersion measure. For pulsars with short periods, the scintillations can completely "smear" the pulses and lead to a sharp dip in the spectrum at low frequencies, as, for example, in the case of the pulsar in the Crab.

11. Dispersion Measure and Distances to the Pulsar. At different frequencies, the pulses are observed at different times. The delay is greater, the higher the frequency. This is due to dispersion on thermal electrons on the propagation path of the radio waves. The dispersion measure is larger, the greater the number of electrons along the path R traversed by the radiation:

$$DM = \int_0^R n_e\, ds = \bar{n}_e \cdot R, \tag{4}$$

where $\bar{n}_e$ is the mean electron concentration along the line of sight. Since the group velocity of the waves depends on the refractive index, and this last depends in a known manner on the frequency, it is easy to determine the displacement in time between the arrival of two different frequencies [9]:

$$\Delta t = DM \cdot \Delta\left(\frac{1}{\omega^2}\right). \tag{5}$$

This frequency dependence is confirmed magnificently by the observations. It enables one to determine the dispersion measure DM from the delay Δt, and by means of it estimate approximately the distance to the pulsars if the mean electron concentration is known. This last is, of course, different in different directions in the Galaxy (on the average, it is equal to 0.03 $cm^{-3}\cdot pc$). The dispersion measure may also be due in part to the source, and in this sense the distances deduced from (4) are upper bounds.*

At low galactic latitudes, the value of the dispersion measure may be very strongly overestimated because of the presence of H II regions of ionized hydrogen. As far as possible, this circumstance is taken into account in the determination of the distances [35, 36].

The distances to the pulsars are estimated to lie in the range from several parsecs to several thousand parsecs. Conversely, if the distances to the pulsars are known from other data, the mean electron concentration in their directions can be determined.

12. Distribution of Pulsars in the Galaxy. Almost all the pulsars lie near the plane of the Galaxy within 500 pc on either side and in a fairly symmetric manner (see, for example, Fig. 4). There is a strong concentration of them toward the plane — just under half of the pulsars are less than 100 pc from the plane of the galaxy. Since the distance indicator is the dispersion measure, this also follows from the plot of the dispersion measure against the galactic latitude [37, 38], which reveals a strong increase in the dispersion measure in a layer of width 10° in the neighborhood of b = 0. A more detailed investigation shows that the plane around which the pulsars are concentrated is in fact 20 pc below the galactic plane, which corresponds to the position of the Sun above the galactic plane.

The distribution of the pulsars with respect to the galactic longitude reveals an increase in their density in the direction toward the center of the Galaxy [39]. Plotted as a function of the distance to the center of the Galaxy, the distribution of pulsars decreases rapidly with increasing "galactocentric radius". Supernova remnants also exhibit a decrease in density with this distance [40].

13. Rotation Measure and Magnetic Field of the Galaxy. Observations of linear polarization of pulsars make it possible to estimate the magnetic field intensity in the neighborhood of the Sun. The Faraday rotation of the plane of polarization determines the so-called rotation measure

$$RM = \int_0^R H_s n_e \, ds = \overline{H}_s \cdot DM, \tag{6}$$

where $\overline{H}_S$ is the mean value of the component of the magnetic field intensity in the direction to the pulsar. The Faraday rotation is found from measurements of the difference between the position angles at neighboring frequencies:

$$\frac{\Delta\theta}{\Delta\omega} \sim \frac{RM}{\omega^2}. \tag{7}$$

A correction with data on the Faraday rotation of other extragalactic radio sources makes it possible to investigate in detail the structure of the magnetic field in the Galaxy [41].

The three most rapid pulsars, 0531 + 21, 0833 — 45, and 1913 + 16, are unique. The first two have been identified with supernova remnants and have the greatest range of radiation, and the third is in a binary system. Study of these pulsars provides the most valuable data for our understanding of the pulsar phenomenon.

14. The Pulsar 0531 + 21 in the Crab Nebula. This pulsar has been identified with the central star ($\sim 17^m$) of the Crab Nebula [42], which is assumed to be the remnant of the supernova in 1054. Its period is the shortest, 0.033 sec, and the rate of change of the period is the greatest, $433\cdot 10^{-15}$ sec/sec, and several strong glitches of the period have been observed. Until recently, it was the only pulsar that also emits optical pulses [43]. Its radiation spans the range 10^{7}–10^{25} Hz, i.e., it is an optical, gamma, x-ray, and radio pulsar.

The Crab Nebula itself has strong synchrotron radiation at all frequencies. Its explanation was attributed to the properties of the central star by Kardashev and Pacini; the latter also saw the possible existence of a pulsar in the Crab [46]. The total

*The absence of a measurable parallax means that the pulsars lie far outside the Solar System.

luminosity in all ranges is $L \sim 10^{37}$ erg/sec (we recall that $L_{\odot} \approx 4 \cdot 10^{33}$ erg/sec), and the main range is in the x-ray. The distance to the pulsar is 2000 pc and the dispersion measure is 57 $cm^3 \cdot pc$, approximately a third of this being due to the nebula or the pulsar itself.

At a distance of 0.4 of the period from the main pulse there is observed an intermediate pulse in the x-ray range of the same intensity as the main pulse. In the radio range, there is a clearly distinguished pre-pulse, this becoming weaker with increasing frequency and disappearing in the optical. The radio pulse precedes the optical by about 39 periods. At all frequencies, the pulses are emitted synchronously. In contrast to the optical pulses, the radio pulses are subject to very strong, at times 100-fold variations in intensity.

15. The Pulsar 0833 — 45 in Vela. It is situated in the radio nebula Vela X, and its age is estimated at a few tens of thousands of years. It has the third shortest period, 0.089 sec, and it also has the third largest derivative of the period: $125 \cdot 10^{-15}$ sec/sec. It is subject to the strongest glitches of the period [28-33]. Like the pulsar in the Crab, it emits in the radio, gamma, and x-ray ranges, and optical pulses have also been observed recently [51]. However, in contrast to the pulsar in the Crab, the pulses of 0833 — 45 in different frequency ranges are displaced in phase relative to one another. the x-ray pulse lags behind the radio pulse by a third of the period, and the main optical pulse (with two peaks separated by 22 msec) also lags behind the radio pulse, being situated symmetrically between two gamma peaks, which are separated by 33 msec. The pulsed emission in blue light corresponds to approximately the 25th magnitude.

16. The Binary Pulsar 1913 + 16. It was discovered in 1974 by Hulse and Taylor [52]. Measurements of the period (the second shortest at 0.059 sec) revealed regular Doppler variations* with a duration of eight hours. These variations are explained by orbital motion in an orbit with semimajor axis approximately equal to $R_{\odot}$ and eccentricity 0.61. The radial velocity corresponding to the orbital motion varies from +100 to —300 km/sec. Both components of the double system are assumed to be compact with masses $\sim 0.13\ M_{\odot}$. The distance to the system is 6 kpc. As ter Haar pointed out [2], the binary pulsar 1913 + 16 puts at our diposal a magnificent relativistic laboratory (see also [53, 54]).

III. Ages of the Pulsars

17. Kinematic Age of the Pulsars. The distribution of the pulsars near the plane of the Galaxy led Gunn and Ostriker [55] to conclude that pulsars are born in the galactic plane and leave it with the passage of time. Study of the proper motions showed [56] that pulsars have high velocities, from 100 to 500 km/sec. The mean distance $\bar{z}$ of the pulsars from the galactic plane is 230 pc, and the mean velocity is $\bar{v} \sim 200$ km/sec [56], which leads to the following estimate for the kinematic age of the pulsars:

$$T = \bar{z}/\bar{v}_z \approx 2 \cdot 10^6 \text{ years}. \quad (8)$$

With a view to establishing indirectly a "genetic connection" of pulsars to other objects, in particular, supernova remnants, it is interesting to compare the frequency of their formation in the Galaxy. Based on data on radio remnants, the rate is approximately one every 50-150 years for supernovae. Judging from the density of the pulsar distribution in the neighborhood of the Sun, one must expect about 10^5 active pulsars in the Galaxy. Then, on the basis of the kinematic age $2 \cdot 10^6$ years, Taylor and Manchester estimated the frequency of pulsar formation at one every 40 years [56]. On the basis of data on the dispersion of the proper motions, Hanson [57] obtained the estimate $4.6 \cdot 10^6$ years for the kinematic age and, therefore, a frequency half as great for the rate of pulsar formation in the Galaxy. From other data, the theoretically calculated frequency of formation of neutron stars is one every 27 years [58], and the frequency of the death of massive stars (with masses $M > 4\ M_{\odot}$) [59] is close to Hanson's estimate for the frequency of formation of pulsars.

The kinematic age of the pulsars is not subject to a strong influence of selection and does not depend on the choice of the distance scale. On the other hand, it does contradict data on the characteristic ages of pulsars (see below). In particular, this leads one to

*The Doppler variations in the periods of the remaining pulsars can be completely explained by the motion of the Earth.

TABLE 1

$\lg\tau$	3	4	5	6	7	8	9
N	1	4	14	38	25	3	1

suspect that the characteristic ages are strongly overestimated compared with the true ages. The considerations in the following subsections eliminate this contradiction.

18. Characteristic Ages of Pulsars. The ages of individual pulsars are usually estimated on the basis of the increase in time of the pulsar periods. It is usually assumed that the pulsars are formed with initial periods close to zero [3]. This assumption also forms the basis of theoretical constructions of pulsar models. Then the age of the pulsar can be determined as the ratio of the period P to its rate of increase $\dot{P}$: $\tau = P/\dot{P}$. Theoretical arguments, and also the presumed decrease of $\dot{P}$ with increasing P lead to the more "reasonable" estimate

$$\tau \approx \frac{1}{2} P/\dot{P}. \tag{9}$$

The characteristic ages calculated in this manner for the two pulsars 0.531 + 21 (1240 years) and 0833 – 45 (11300 years), which are identified with supernova remnants, agree reasonably with the ages of these remnants determined by different methods (note that these pulsars have the shortest periods).

In Table 1, we give the distribution of the 86 pulsars with known values of $\dot{P}$ with respect to the characteristic age τ [12]. If the characteristic ages did reflect correctly the "true" ages of the pulsars, their distribution would be uniform with respect to τ, at least at small τ. This follows under the assumption that the pulsars are formed with small initial "periods and ages" and evolve in approximately the same way. But the distribution in Table 1 does not correspond to the expected proportionality between the number of pulsars and the length of the interval τ and indicates that the characteristic ages are strongly overestimated compared with the true ages. The mean value of the characteristic age is $\tau = 5\cdot 10^7$ years [12], which is an order of magnitude higher than the kinematic age.

19. With what Periods are Pulsars "Born"? This problem was drawn to my attention by Ambartsumyan in 1970. At that time, the number of pulsars was already 55 and one could definitely conclude that the idea that all pulsars are born with very small initial periods is incorrect [60].

The solution of this problem is based on the known distribution N(P) of the pulsars over the periods and the following assumptions:

1) The required distribution $n(P_0)$ of the pristine pulsars with respect to the initial values of the periods is stationary in time.

2) The pulsar periods increase with a certain mean (constant) rate $a = \bar{\dot{P}}$.

Together, these assumptions of course mean that the observed distribution N(P) is stationary in time. If the first assumption is natural, the second does require verification. In accordance with 2), an as yet undetermined time scale a is introduced.

Omitting here the mathematical side of the problem, we give its final solution as applied to the present case. The required function n(P) is given by the expression

$$n(P) = \begin{cases} \dfrac{d}{dP} N(P), & P < T_0, \\ \dfrac{d}{dP} \{N(P - T_0) + N(P)\}, & P > T_0, \end{cases} \tag{10}$$

where T_0 is the value of P corresponding to the maximum (if such exists) of the distribution N(P). The case $P > T_0$ means that the function N(P) for $P < T_0$ must be shifted to the right by the amount T_0, added to the function N(P) for $P > T_0$, and differentiated. Below, we shall denote the parameter corresponding to the initial value of the period by the

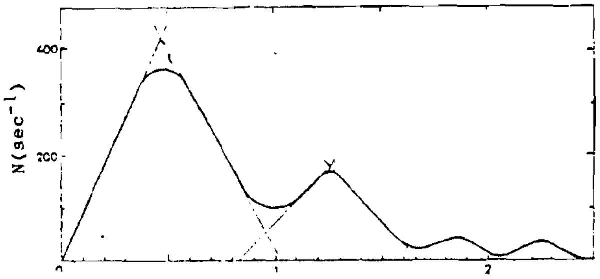

Fig. 1

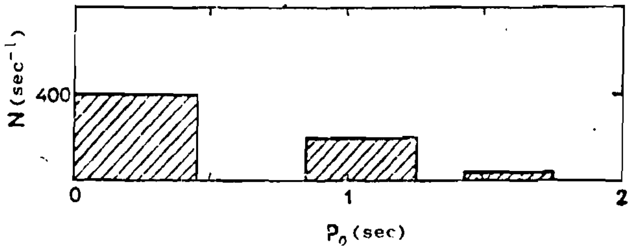

Fig. 2

letter P_0. We now turn to a discussion of the observed distribution N(P) of the pulsar periods.

20. Distribution of the Pulsar Periods. Figure 1 shows the distribution of the known 320 pulsars with respect to their periods. It is characterized by the presence of two maxima at p = 0.5 sec and 1.25 sec. The third and fourth maxima are due to the very small number of pulsars (ten in each), so that they should not be taken into account. The distribution was constructed in a special method that eliminates known inaccuracies in the construction of histograms.

The two clearly expressed peaks in the distribution of the pulsar periods was first discovered by the author in 1970, and their existence has been confirmed by the accumulation of new pulsar data. Taylor and Manchester [3] rule out an influence of selection factors on the profile of the (first) maximum and on the appreciable dip in the region $P \approx 1$ sec recently found independently in [17, 61].

The distribution N(P) can be well represented as a sum of two "triangle" distributions, these being shown by the straight lines in Fig. 1. Both the triangles are isosceles, ≈220 pulsars corresponding to the first and ≈80 to the second. The solution to the problem of finding the function $n(P_0)$ requires that they be considered separately as two independent groups.

If the absence of pulsars with large values of the periods means that pulsars have a definite lifetime, after which they "switch off", the comparatively small number of pulsars with short periods is evidently a direct indication that not all pulsars are formed with near-zero initial periods but only a small fraction of them.

21. Distribution of the "Newly Born" Pulsars over the Periods. Application of formulas (10) to the distribution N(P) shown in Fig. 1 leads to the following result. The pulsars of the first group (corresponding to the first maximum) are formed with initial periods that take values in the interval $0 < P_0 < T_0$ with equal probability. The time of active life of these pulsars is T_0, i.e., it is equal to the time during which the period of a pulsar increases, say, from 0 to T_0 (at the rate a). The pulsars of the second group (corresponding to the second maximum in the period distribution) are formed with initial periods in the interval $0.8 < P_0 < 1.25$ sec, also with uniform probability. The time of their active life is of order 0.45 sec [sic] $\approx T_0$.

The described distribution of the newly born pulsars with respect to the initial periods is shown in Fig. 2. This also includes the third group of pulsars corresponding to the third maximum in Fig. 1. The possibility cannot be ruled out that pulsars of the second group are part (40%) of the pulsars of the first group that for a time (of ~0.3 sec) have ceased their pulse activity. On the basis of other arguments, we see that this is not so.

Note that if all pulsars were formed with zero initial periods, the function $n(P_0)$ would have to be described by the delta function $\delta(P_0)$.

22. Dependence between the Period and its Derivative. In Fig. 3, we have plotted the values of P and $\dot{P}$ for 86 pulsars with known values of $\dot{P}$ [12]. The values of $\dot{P}$ vary in a fairly wide range from 10^{-16} to 10^{-13} sec/sec. It cannot escape notice that some

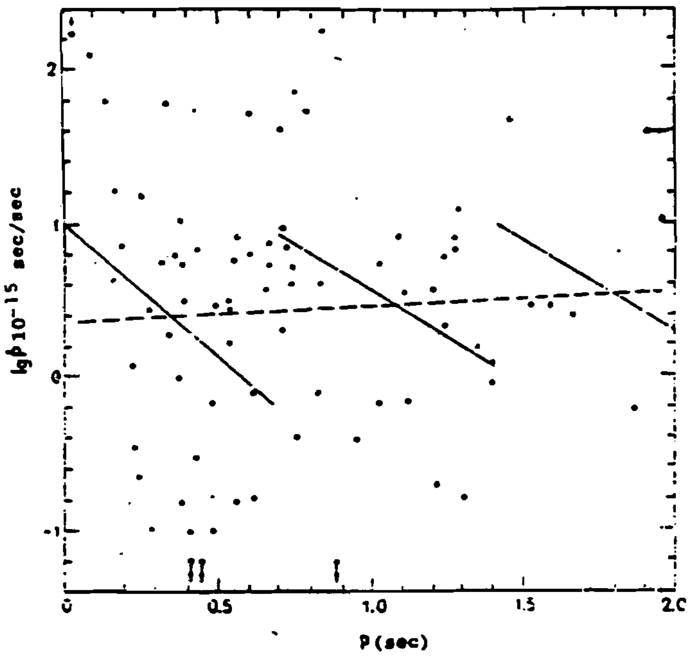

Fig. 3

TABLE 2

Group	I	II	III
$\overline{\tau}$	3.6	3.2	3.8
T_0	4.4	4.3	4.0

pulsars with very short periods have especially large $\dot{P}$. This suggests that the rate of increase of the period decreases with the increase in the period. Note that from a physical point of view an inverse proportionality between $\dot{P}$ and P is more reasonable. With regard to the correlation between these quantities, different authors differ [2, 3]. The dashed straight line in Fig. 3 indicates a weak increase in $\dot{P}$ with increasing P found by the method of least squares.

Bearing in mind the presence of the three independent groups of pulsars noted in the previous subsection, we consider independently the separate parts of the $\dot{P}$ — P diagram corresponding to the intervals of the periods 0-07, 0.7-1.4, and 1.4-2.1 sec. For each of these groups of pulsars in Fig. 3, straight lines approximating the dependence of $\dot{P}$ on P were drawn by the least-squares method. We now see a clear decrease in $\dot{P}$ as a function of P for each of the three groups. This, in its turn, is an argument in favor of these being independent groups of pulsars.

It is interesting that the slopes of these three straight lines in Fig. 3, like the mean values $\dot{P}$ for each group, are fairly close to each other. They correspond approximately to the value $a \approx 3.7 \cdot 10^{-15}$ sec/sec.

23. On the True Ages of Pulsars. With a view to obtaining estimates of the pulsar ages that are closer to the true ages, it is necessary to review the definition of the characteristic ages, assuming, for example, that the pulsars are formed with initial periods equal to 0, 0.7, and 1.4 sec, respectively, for the three groups. Then for the pulsars of group I the characteristic ages (9) remain unchanged, whereas for groups II and III they are significantly shortened.

The characteristic ages $\overline{\tau}$ calculated with this correction are given in Table 2 (in millions of years). In the calculations, we eliminated seven pulsars from group I, which contains 42 pulsars, and two pulsars from the second group, which contains 29 pulsars, their characteristic ages being an order of magnitude and more greater than the corresponding mean values.

In the second column of Table 2, we give the mean time T_0 of the active life of the pulsars, the corresponding times $T_0 \approx 0.5$ sec for the values a = 3.6, 3.7, and 4.0 (10^{-15} sec/sec), which are the mean values $\dot{P}$ for each of the three groups. We see that the characteristic ages are similar for the three groups and close to the mean active life of pulsars, which is $T_0 \approx 4.4 \cdot 10^6$ years. Note that the true ages of the pulsars must be taken at half this value, since they are formed with periods that are not equal

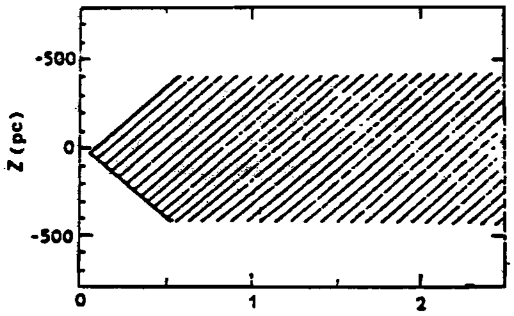

Fig. 4

to 0, 0.7, and 1.4 sec, as was assumed in the calculations above, but with periods distributed uniformly in the corresponding intervals.

Thus, bearing in mind that the pulsars are not formed with zero values of the initial periods, the contradiction between their kinematic and true (or characteristic) ages can be eliminated.

24. Period vs Distance from the Galactic Plane. If the ages of the pulsars really are approximately the same for all three groups, and if they are formed in the galactic plane and leave it on the average with equal velocities, we must expect that the mean distances of the pulsars from the galactic plane is the same for all groups.

Figure 4 shows the plot of the period against the distance from the galactic plane for 147 pulsars with known z (data taken from [12]). Almost 95% of the pulsars are strikingly situated in the hatched region in Fig. 4, which has the shape of a "sharpened pencil", the sharpened tip having clearly defined edges. Within the tip, with $P < 0.5$ sec there are distributed 65 pulsars, whereas there are seven pulsars in front of the tip. The pulsars furthest from the tip are 0531 + 21 (in the Crab) and the binary pulsar 1913 + 16. The pulsar in the Crab is comparatively young and was therefore "born" with this separation from the galactic plane. The pulsar Vela X is at the point of the tip.

The "pencil" shape of the plot corresponds to the idea that pulsars of group I are formed in the galactic plane with periods in the interval 0-0.5 sec and leave it with the passage of time with a velocity ~100 km/sec. The edge of the pencil for $P > 0.5$ sec also corresponds to a mean velocity of separation from the plane of ~100 km/sec. The circumstance that the pulsars of the second and third groups are not situated further from the galactic plane than those of group I means that they are not "descendants" of the latter in the sense suggested in §21.

It is interesting that the pulsar distribution has the same pencil shape when $-\log \dot{P}$ is plotted against the distance from the galactic plane. Once again, the pulsar in Vela X with $\log \dot{P} = -12.5$ is at the point of the tip, and the pulsar in the Crab and and the binary pulsar are again outside the region of the pencil.

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