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ON THE CONTINUING STELLAR FORMATION IN THE CENTRAL REGIONS OF SOME GLOBULAR CLUSTERS AND THEIR RELATION TO PULSARS

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CONTINUING STELLAR FORMATION IN THE CENTRAL REGIONS OF SOME GLOBULAR CLUSTERS AND THEIR RELATIONSHIP TO PULSARS

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The properties of the central regions of massive globular clusters and the problem of the discrepancy between the predicted and observed quantities of gas in them are discussed. Based on a number of observational aspects the hypothesis is advanced that star formation continues in their central regions by means of gas either released during the evolution of stars in these regions, or trapped by the central region of globular clusters when the latter passes through the dense medium near the center of the Galaxy. To confirm the hypothesis of continuing star formation nine globular clusters are indicated at distances less than 1000 ps from which radio pulsars or x-ray sources are observed. Arguments are given in favor of the fact that they could have been formed relatively recently in closed pairs of the central regions of these globular clusters, and then at the stage of "supernova"bursts they were ejected from there with velocities of $\gtrsim 100$ km/s. Thus, a natural explanation is obtained for the appearance of pulsars at high galactic latitudes. /3*

1. Recently the researchers have been paying more and more attention to the central regions of globular clusters. This has been promoted by the detection from certain globular clusters of x-ray radiation which sometimes bears the nature of short-term ($\Delta t \sim 10$ s), powerful ($P_{XR}^{1-10\ kev}$ to $10^{37-38}\ \frac{erg}{s}$) bursts [1]. It has been found that x-ray sources are encountered only in massive globular clusters with a well isolated central region. According to publications [2,3], such globular clusters have a nuclear radius of $r_c \leq 0.5$ ps, central stellar density $\rho_c \geq 10^5\ M_\odot/ps^3$, and concentration index $c \equiv \log \frac{r_t}{r_c} \geq 1.7$, where r_t--King's tidal radius (see, for example, [4]). It was also noted that the globular clusters that are x-ray sources are located in the upper right quadrant on the plane "velocity of drift-inverse time of relaxation" [5], which indicates the /4

*Numbers in margin indicate pagination in original foreign text.

full mass of these globular clusters $\geq 1.5 \cdot 10^5 M_{\odot}$ ($\gamma_{drift} \geq 25$ km/s, $\tau_{relax.} \leq 10^8$ years). As yet it is not quite clear whether all the globular clusters with the aforementioned properties are x-ray sources (see, for example, [6, 6a]), but if further observations confirm this, then one can expect an even more powerful x-ray radiation from the close compact galaxies of the type, for example, Andromeda satellites NGC 205 and MZ2 which are both more massive, and more concentrated than the richest globular clusters.* Unfortunately, now it is impossible to indicate with confidence from precisely which regions of the globular clusters or compact galaxies one should expect x-ray radiation. However there are a number of theoretical arguments in favor of the fact that the x-ray sources are located in their central regions. It is not excluded that the highly-dense central regions of the far-evolved massive globular clusters can in certain relationships be similar to the central regions of compact galaxies or giant spheroidal systems of the type Cen A or M87. The latter, by the way, are strong x-ray sources [8,9]. At the same time, with all probability, their radiation consists of radiation of the compact central source and extended component. The nature of both of these components is still not clear. Publication [10] for example, hypothesizes that the extended x-ray source in M87 presents from itself a sum of radiation from numerous (several thousand) globular clusters into the halo of this giant E-galaxy. The question as to the nature of the extended x-ray radiation is not clear even for the closest galaxies: Nebula Andromeda [11] and Magellanic Clouds [12]. In all probability it will be successfully solved only with an improvement in the angular resolution of the x-ray apparatus which is still less than several angular minutes. /6

2. Thus, research with good resolution of the central regions, rich globular clusters, is not only of great importance from the viewpoint of the structure of the actual clusters and the nature of the x-ray sources in them, but also from the viewpoint of the problem of the nature of nuclear regions and the more massive spheroidal stellar systems--compact and elliptical galaxies.

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*Publication [7] gives the upper limits of x-ray radiation from certain dwarf galaxies of the local group. But precisely for these weakly-concentrated systems the x-ray radiation must not be considerable (by analogy with the situation in the globular clusters).

a) By now there is unfortunately not a lot known about the properties of the central regions of globular clusters. The fact is that due to the high optic surface brightness of these regions it is necessary to make observations with exposures < 1 minute and with angular resolution better than several angular seconds. The first observations of such type have already appeared. For example, in publication [13] it is shown that the central region ($\sim 10^m$) of globular cluster M15 apparently has a quasi-blue color*, corresponding to radiation of stars of the spectral classes BZI-AOI. It is true that in work [14] no change in the color in M15 with the radius was found, although an excess of surface brightness is noted in the center of the cluster in relation to the isothermic distribution. The authors attribute this excess to the effect of the central compact body with $M \approx (800 \pm 300) M_\odot$. Publication [15] has obtained from the x-ray satellite ANS brightness distribution in the range 1550-3300Å in the globular cluster 47Tuc. The authors note that the mean color indicator $C_{2200-3300Å}$ is not altered with the radius, while its "jumps" in individual directions are apparently linked to the contribution of radiation from individual red giants in the central region of this cluster. Publications [16, 3] have obtained photographs with minute exposure of x-ray globular clusters NGC 6624, 6440 and 6441 according to which the authors pinpointed the distribution of surface brightness in the central regions of these clusters. We note also that in the central region of the globular cluster M15 on the photographs with short exposure (Rosh on 106 cm telescope, Pic du Midi with 15-second exposure, and V. P. Goranskiy, A. S. Sharov and S. Yu. Shugarov on 70-cm GAISh telescope with 2-10 minute exposure) certain formations are visible which coincide in position with the blue spot found by V. P. Goranskiy. Whether these formations have a stellar or nonstellar nature is not yet clear.

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Publication [17] in the central region of the rich cluster M13 found a large number of stars (about 30) over the horizontal branch of the pattern M_V, B-V. Such stars in certain globular clusters and dwarf galaxies were known previously in a small quantity [18]. On the diagram they are arranged in that

*Still earlier V. P. Goranskiy (GAISh)[P. K. Shternberg State Astronomical Institute] obtained on a 70-cm reflector in Moscow a photograph of M15 on color film with 1.5-hour exposure, on which a blue spot is visible in the center of the cluster. E. A. Dibay (GAISh) obtained spectra of this formation on which a blue continuum was isolated without signs of any lines.

place where the Cepheids of the population II are, i.e., the objects of the spherical component, but they have with the same period of change in brilliance greater luminosity than the normal Cepheids II--these are the so-called anomalous Cepheids. As yet it is not possible to explain such stars on the basis of the hypothesis on the normal stellar evolution. It is not excluded that they produce a branch of giants that recently converged with the main sequence as occurs in the young scattered clustors where star formation continues even now. However, the hypothesis on the continuing star formation in the central regions of rich globular clusters requires the presence there of a sufficient quantity of dense gas. Therefore the problem of finding gas in the central regions of the globular cluster is of fundamental importance. However, this question, despite the research of the past years, is still not yet completely clear.

b) In publication [19] an attempt was made to search for the line H_α from 26 globular clusters with the help of a Faori-Pero interferometer. The results, in general, confirmed the data of previous works--in the globular clusters the gas was not greater than several solar masses. A report appeared [20] on finding from nine globular clusters in ranges λ=11 and 3.7 cm radio radiation on the level $5\cdot10^{28}$-$3\cdot10^{30}$ erg/sec. The radio sources, in all probability, are not point with fairly sharp spectra. This radio radiation is hardly linked to radiation of hot plasma in the globular clusters, since no correlation between the radio power and the quantity of gas defined with respect to H_α is observed. /9

Thus, the observational conclusion about the small quantity of gas in the globular cluster is contradictory to the theoretical estimates of the gas quantity that could be accumulated in the globular cluster in the space of 10^8 years (the time between the successive passages of the globular cluster through the plane of our Galaxy) due to the discharge of substance by the evolving stars. It was expected that during this time in the rich globular cluster no less than 100 $M_\odot$ of gas should accumulate. In publication [21], for example, it is estimated that this gas is accumulated in the Galaxy, mainly due to the discharge of substance by the planetary nebulae ($\sim \frac{0.15\ M_\odot/\text{year}}{\text{to Galaxy}}$), OV and red giants ($\frac{0.15\ M_\odot/\text{year}}{\text{to Galaxy}}$) and during bursts on red dwarfs. In the globular clusters the planetary nebulae are very rare (for example, one is known in the central region of M15), however there can be a lot of red giants and red dwarfs in them. Therefore one can expect the rate of gas accumulation to be on the level of 10^{-6} $M_\odot$/year. (This also yields in 10^8 years about 100 $M_\odot$). How then can one explain the discrepancy between the observational and the expected quantity of gas in the globular cluster? Different opinions are advanced in the literature on this subject. We will list some of them.

1. The gas in the globular cluster is heated to high temperatures ($\sim 10^6$ K) due to either bursts of SN [22] or radiation of hot stars [23], and it emerges from the cluster in the form of an isothermic wind.

2. The gas is expelled from the globular clusters during their periodic passages through the dense medium of the galactic disk , or by means of the dynamic effect of the interstellar medium of the galactic halo. According to the estimates of [22], for the globular cluster moving in relation to the medium with $v_{gl.cl.}$=200 km/s, the density of the medium that is necessary for ejecting the gas from it must be $\sim 5 \cdot 10^{-2}$ cm^{-3}. Here it was assumed that $v_{drift} \approx 50$ km/s, /10
the rate of gas loss by the stars in the globular cluster α-10^{-11} per year per unit of mass, and the surface density of the stars in the center of the cluster $\sigma_c = 10^5 M_\odot/ps^2$. The condition for the ejection of gas from the globular cluster is written in the form [22]:

$$\rho_{medium} \; v^2_{gl.cl.} > \alpha \; \sigma_c \; v_{drift}.$$

We note that the authors of [22] selected parameters of globular clusters that are fairly extreme towards an exacerbation in the conditions for gas ejection. If one takes less massive and less concentrated clusters, then $\rho_{medium} \approx 5 \cdot 10^{-3}$ cm^{-3} will be sufficient for ejection, which is noticeably lower than the available estimates of substance density in the halo and coronas of the spiral galaxies. For example, according to [24], $n_{halo} \approx \frac{n_o}{(r + r_o)^2}$, where

$$r_o \approx 20 \text{ kps and } n_o \approx \frac{2 \cdot 10^{-25} g/cm^3}{1.6 \cdot 10^{-24}} \approx 10^{-1} \text{ cm}^{-3}.$$

It is true that we do not know which part of this substance is in the form of a gas and which is in the form of dwarf stars. Apparently, the quantity of ionized gas in the coronas of spiral galaxies is not more than ~10% of the total amount of substance (see, for example, [25]).

We note here that in the strongly concentrated globular clusters gas ejection is strongly impaired in the central regions as compared to the peripheral. This problem is similar to the situation in the galaxies discussed as applied to their movement through the intergalactic medium of rich clusters of galaxies in a number of works (see [26, 27]). In the central regions of massive globular clusters there can occur not ejection but accumulation of gas released by the stars, especially in those cases where the cooling time of this gas is less than the time for its escape (see [28]). It is also not excluded that certain globular clusters occurring in highly extended orbits /11 into the central regions of the Galaxy rich in gas can trap the external gas in the gravity pocket of its center. Perhaps, this is precisely associated with the fact that we obtained from preliminary data of the dependence of the power of the x-ray sources in the globular cluster on the distance of the globular cluster from the center of the Galaxy: $P^{max}_{XR\,(2-10\ kev)} \sim R^{-2}$ (see fig. 1). We note that the dependence of the substance density on the distance to the center in the spherical component of the corona or halo of the galaxies bears a similar (isothermic) nature: $\rho \sim R^{-2}$.

3. The gas of the globular cluster escapes into its central region where it either grows into a massive compact body (perhaps, a black hole with $M \geq 10\ M_\odot$), or, by accumulating into dense clouds is turned into stars. The possibility of the existence in the center of rich globular clusters of black holes and the concomitant phenomena have been extensively discussed in the literature [5, 29] due to the detection of powerful bursts of the x-ray sources in certain clusters and in the region around the galactic center. (As of now in the literature bursts are linked definitely only to three globular clusters: NGC 6624 (ZU 1820-30), NGC 1851 (MX 0513-40) and the globular cluster found by Liller in the red rays (MXB 1730-335). For globular clusters NGC 6440, 6712, 6388, 6541, 5904 and 2298 such a link has not been strictly proven. In globular clusters NGC 7078, 6441 and 5946 the x-ray radiation does not have a burst-like nature). We will dwell in more detail on the possibility of continuing star

formation in the central regions of rich globular clusters.

3. We have already mentioned this possibility at the end of point a) in section 2. Over 10 years ago this problem was touched upon in the works of N. N. Kholopov [30, 31] in relation to the criticism of the reliable detection in certain globular clusters of dust complexes. In the opinion of N. N. Kholopov the data of publications [32,33] on the existence in the central regions of the globular clusters M4, M10, M14, and NGC 6171 of dust clouds are erroneous and /12
are simply linked to the nonuniform distribution of bright stars. The effect can be real only in globular cluster M13. Therefore the conclusions [33] on the possible existence in the central regions of the globular clusters of stars of the second generation, and their link to the blue stars for the continuation of the main sequence (blue stragglers) are doubted. However, publication [19] again recalls this possibility. The continuing process of star formation in certain globular clusters could also be judged according to a number of concomitant phenomena, such as for example, IR radiation, molecular lines and lines of excited hydrogen, nonthermal radio radiation, the presence of dust complexes, and so forth, i.e., all the components observed in the NP zones or young scattered clusters in our Galaxy. One can also expect bursts of SN of the first type (by analogy with the E-galaxies), and this means also after the outburst phenomena: residues of supernova SNR, radio and x-ray pulsars. We have already spoken of the radio radiation from certain globular clusters. In the literature preliminary reports have also appeared on finding in certain globular clusters IR radiation (M15, M13, M5 and M3) and dust complexes, although all of this requires confirmation by new observations. It is difficult to expect to see SN and SNR in the globular cluster in light of the rarity of bursts and the short duration of these phenomena. In fact, if one considers that in the entire Galaxy SN burst once even in 30 years, then in the globular clusters whose summary mass hardly exceeds 10^{-3} of the mass of the entire Galaxy, this time reaches already $3 \cdot 10^{4}$ years. And if one considers that such bursts of SN are expected only in the central regions only of rich clusters, then we obtain an even greater time interval $\sim 10^{6}$ years.

However, if one assumes that as a result of the burst of SN a neutron star is always formed which can be observed as a radio pulsar, then the situation is radically altered. According to the data on the around 150 single radio pulsars that have been found up to now [34] one can draw the conclusion that their average age $\tau = \frac{1}{2}\frac{P}{\dot{P}}$ reaches $\sim 10^7$ years (fig. 2) and this means that one can attempt to find single radio pulsars in the globular clusters. Here, however, it should not be forgotten that the observations result in the conclusion that the radio pulsars possess high natural velocities that reach hundreds of km/s [35].* Such velocities are acquired by the PSR either in the process of rupture of closed pairs in whose composition they are formed (see, for example, [37]), or due to the slight asymmetry of the very powerful radiation of the PSR immediately after its formation [38]. It is also not excluded [39] that the velocity is acquired due to the short-term (in relation to the orbital period) ejection of the mass during the PSR burst that is a less massive component of the closed pair. This means that the PSR in moving with velocity of 100 km/s can escape from the site of its emergence in $\sim 10^7$ years to a distance reaching 1000 ps. And if the PSR was formed even in the central region of a rich globular cluster, then it should be sought already outside the cluster since the velocity of 100 km/s is quite sufficient to escape from the globular cluster. Having assumed a distance to the globular cluster of $\sim$10 kps, and considering that the PSR can escape from its center to a distance of 1 kps, it is easy to obtain an estimate of the angular distance at which one should look for the pulsars that have escaped from the globular cluster: 5°. The coordinates and distances for the globular cluster were taken from monograph [40], and for pulsars--from publication [34]. The cases of the satisfactory coincidence of coordinates and distances are given in the table. In seven cases these are radio pulsars, and in two cases--x-ray sources.** /14

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*For the x-ray pulsar Her X-1 a high natural velocity was also obtained according to the measurements of its position on the photoplates (see, for example, [36]).

**A. S. Melioranskiy and M. I. Kudryavtsev also noted that the unidentified high-latitudinal x-ray ZU sources have a certain tendency to be located close ($\sim$5°) to the globular cluster, and N. Ye. Kurochkin was the first to draw attention to the proximity of the globular cluster M13 to the x-ray pulsar Her X-1.

In Table 1 attention is drawn to the fact that in eight out of nine cases we have globular clusters of the second type, according to publication [41]. Type II includes the globular clusters which, if one judges by the type of diagram color-amount and by a number of other signs, have a lower age as compared to the globular clusters of type I.

Of course , due to the poor accuracy in determining the distances both of globular clusters and the PSR among the "pairs" we selected there can also be random ones. If one constructs the distributions of globular clusters and PSR according to the distance from the sun (table 2, c); fig. 3, according to $|z|$ -- coordinate (table 2, a); fig. 4 and according to $|\ell^{II}|$ (table 2, b); fig. 5, then it is evident that the projection density of both the globular cluster and the PSRR is fairly great, especially in the direction towards the galactic center with $|\ell^{II}| < 10°$. Therefore in this region without reliable estimates of the distances it is impossible to be positive about the physical unity of the PSR and globular cluster, since the probability of a random projection is great.

The hypothesis about the possible discharge of the PSR from the globular cluster makes it possible in a natural way to solve yet another problem. As is apparent from fig. 4, the distribution of PSR with respect to $|z|$ is stretched all the way to 2 kps. If the PSR emerged only with bursts of SN only in the plane of the Galaxy, and its escape from there was governed by velocities obtained during the rupture of closed pairs, then a correlation should be observed between $|Z|$ and the ages of the PSR. However there is no such correlation (fig. 6). Therefore the question arises as to how the PSR occur at high $|\ell^{II}|$. But this question can be answered simply if one adopts the hypothesis on the con- /15
tinuing star formation in the central regions of the globular clusters. In this case, the PSR simply were carried to high $|\ell^{II}|$ by globular clusters, and then flew out of them. One can expect that behind the massive globular clusters there stretches a tail of pulsars discharged at different times. But, unfortunately, we cannot observe them all since, first, pulsars have a fairly narrow beam pattern of radiation ($\sim 10°$) and second, they strongly attenuate in power the radio radiation with time.

Thus, the question as to the possible continuing star formation in the central regions of massive old globular clusters has been raised, but of course not answered. Its answer requires new studies both in the optic and in other ranges with good angular resolution. And here we again see an analogy with the central regions of certain types of galaxies in which star formation in this epoch is also possible (for example [42]). In our discussions we have not touched upon the question of how the problem of star formation and the problem of bursting x-ray sources in the globular cluster can be linked. Although we also do not have the answer to this question, however, it is not excluded that the phase of burst activity can be a short-term stage in the evolutionary development of relatively young, massive stars. Most likely, this stage is linked to the formation in closed pairs of compact objects of the white dwarf type with strong magnetic field or neutron star. At this moment it is not possible to choose between the specific mechanisms of such burst activity in the x-ray range. This can be in addition to the different type of nonstationary accretion also the activity of the burst type on the sun, intensified tens of thousands of times due to the hundred times stronger magnetic fields (see, for example, [43]).

In conclusion the author expresses sincere gratitude for the useful notes /16
and numerous discussions of the colleagues of GAISh: N. N. Samus', A. V. Mironov, A. M. Cherepashuk, P. N. Kholopov and Yu. N. Yefremov, and for the presentation of unpublished materials--V. P. Goranskiy and A. S. Melioranskiy.

TABLE 1

gl.cl. PSR	l^{II}	b^{II}	R_{kps} *)	Δl_{ps}	Notes
NGC 6539 PSR I8I8-04	020.80 025.5	+06.78 04.70	3,6 3,2	3I4	globular cluster type II
NGC 6544 PSR I8I3-26	005.83 005.2	-02.22 -04.80	38 3,5	I63	globular cluster type II
NGC 6553 PSR I8I3-26	005.25 005.20	-03.06 -04.80	3,3 3,5	I00	globular cluster type II
NGC 6626 PSR I8I9-22	007.80 009.40	-05.58 -04.3	5,8 5,7	I28	globular cluster type II
NGC 67I2 PSR I846-06	025.34 026.70	-04.32 -02.40	5,7 5,7	208	globular cluster type II, x-ray bursts
NGC 6205 HzHer	059.00 058.00	+40.9I +35.00	6,3 6	630	globular cluster M13, type I
NGC 6I2I Sco X-I	350.99 0.00	+I5.96 24.00	2,0 2,0	350	globular cluster M4, type II
NGC 6624 PSR I8I3-26	2 8 5.2	- 7.92 - 4.8	5,0 3,5	270	globular cluster type II, x-ray bursts
NGC 6388 PSR I727-47	345,54 342.60	-06.74 -07.7	6 5,9	3I0	globular cluster type II, x-ray bursts

*The accuracy of determining distances both to the globular cluster and to the PSR is not better than 30-50%.

TABLE 2

a)

$\|z\|$ ps	0–I00	I00–200	200–300	300–400	400–500	500–600	600–700	700–800	I kps
N_{PSR}	59	25	20	I9	II	2	3	2	2

$\|z\|$ kps	0–I	I–2	2–3	3–4	4–5	5–I0	I0–I5	I5–20	25
N gl.cl.	3I	25	I2	5	8	I3	8	5	9

b)

$\|b^{II}\|$	0–I0	I0–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90
N_{PSR}	I20	8	3	7	3	2	3	0	I
N gl.cl.	56	32	I3	8	I2	I	I	6	I

c)

R kps from e	0–I	I–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–I0	I0
N_{PSR}	37	I6	I9	I3	I0	I3	8	8	I0	5	6
N gl.cl.	0	0	3	7	8	II	I0	I0	9	8	43

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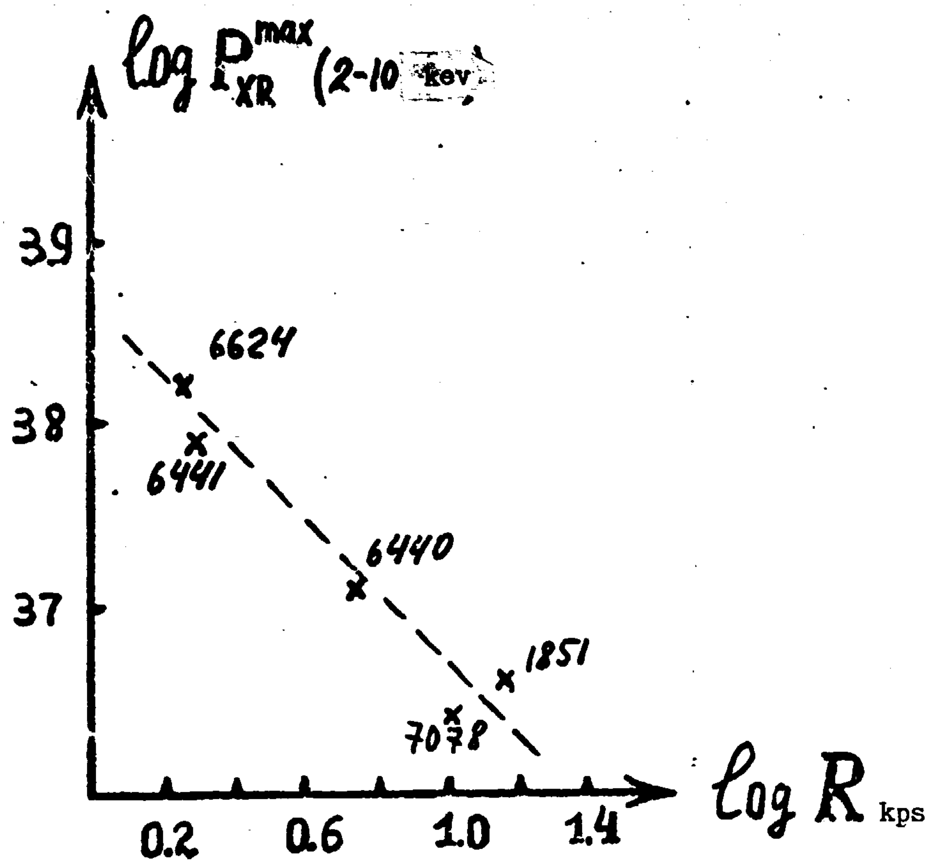

from nucleus of Galaxy

Figure 1. Approximate Relationship between Distances (kps) of Globular Cluster from Center of Galaxy and Summary Power of X-Ray (2-10 kev) Sources in Them:

$$\log P_{XR\,(2\text{-}10\ \text{kev})}^{max} \approx -2 \log R_{kps} + 38.6$$

(Data were taken from the literature, numbers of globular clusters are given for NGC).

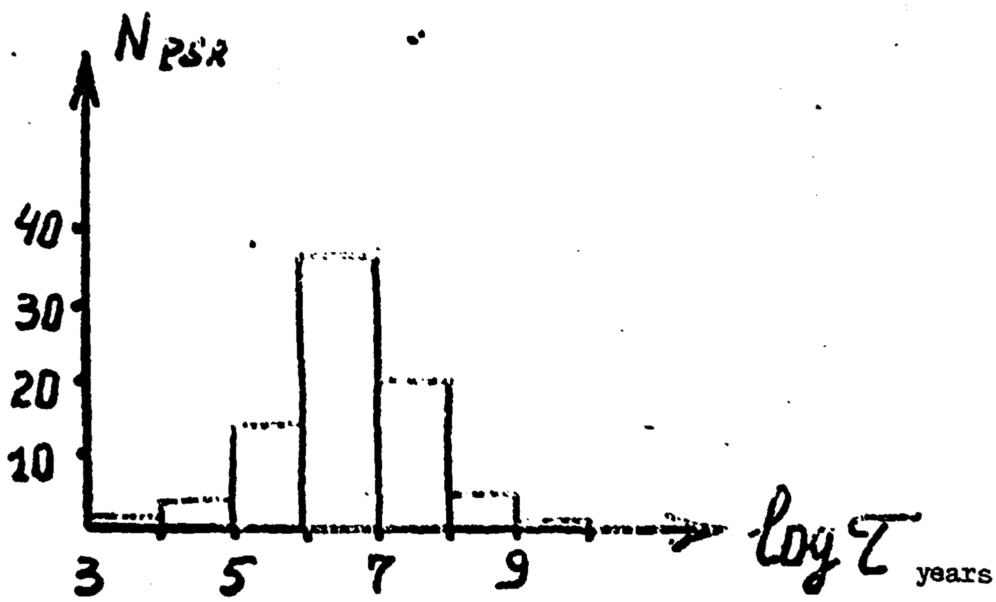

Figure 2. Distribution of Radio Pulsars with Respect to Lifetime $\tau = \frac{1}{2}\frac{P}{\dot{P}}$.
Data taken from publication [34].

/23

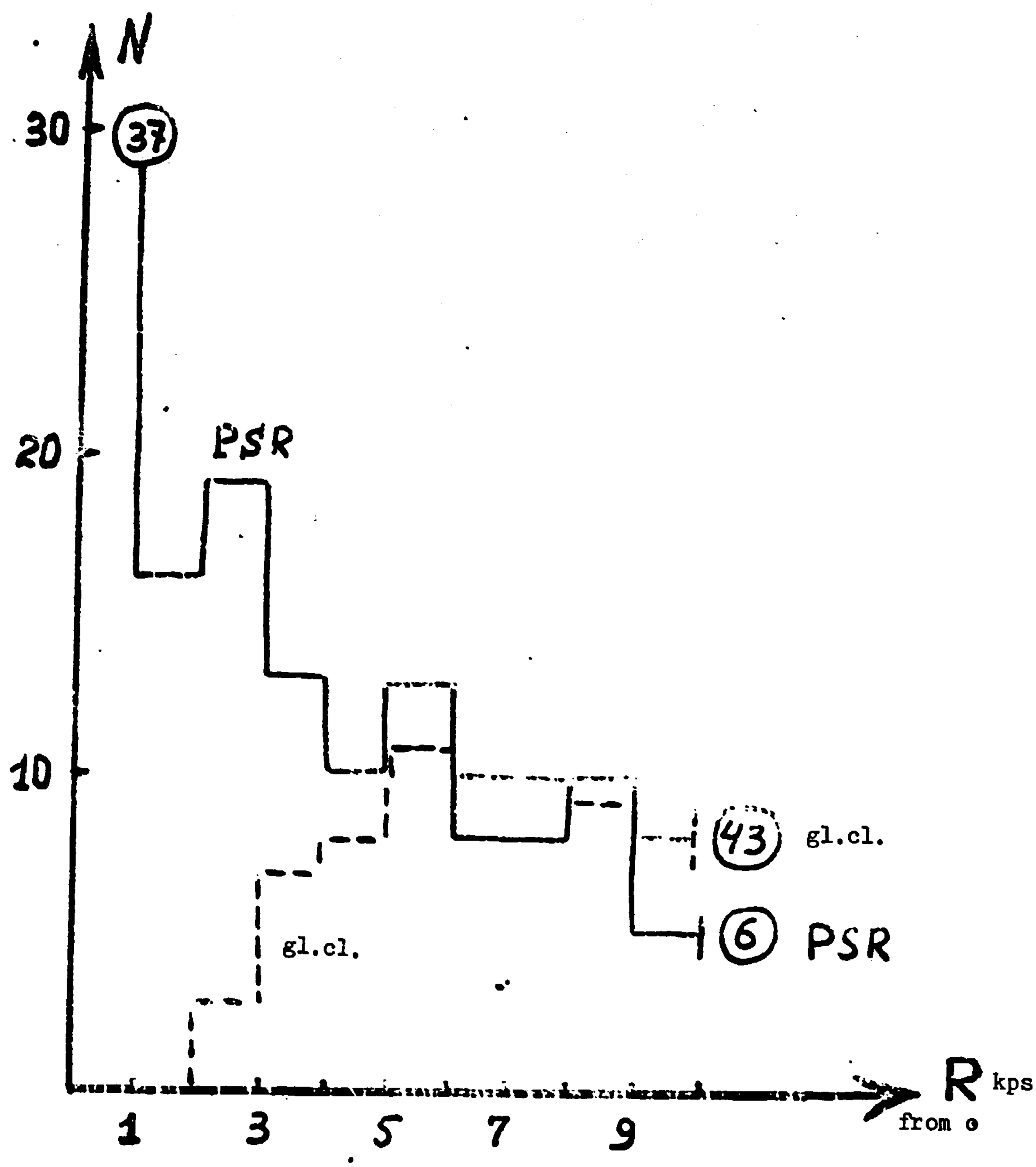

Figure 3. Distributions of Radio Pulsars and Globular Clusters with Respect to Distance from Sun. Date taken from publications [34] and [60].

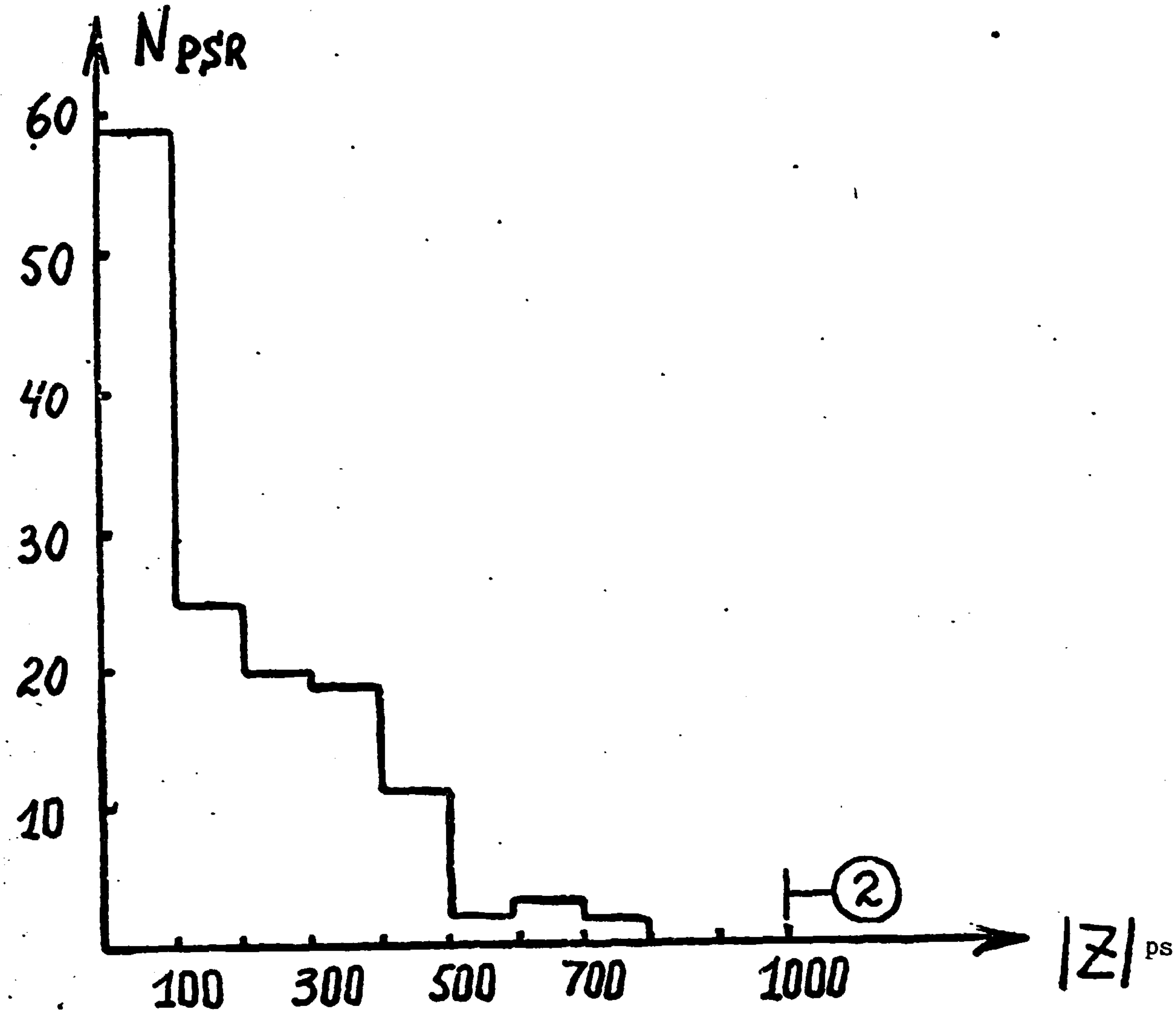

Figure 4. (continued on next page)

Distributions of Radio Pulsars and Globular Clusters according to Distance above Plane of Galaxy. (Z--coordinate). Data taken from publications [34] and [60].

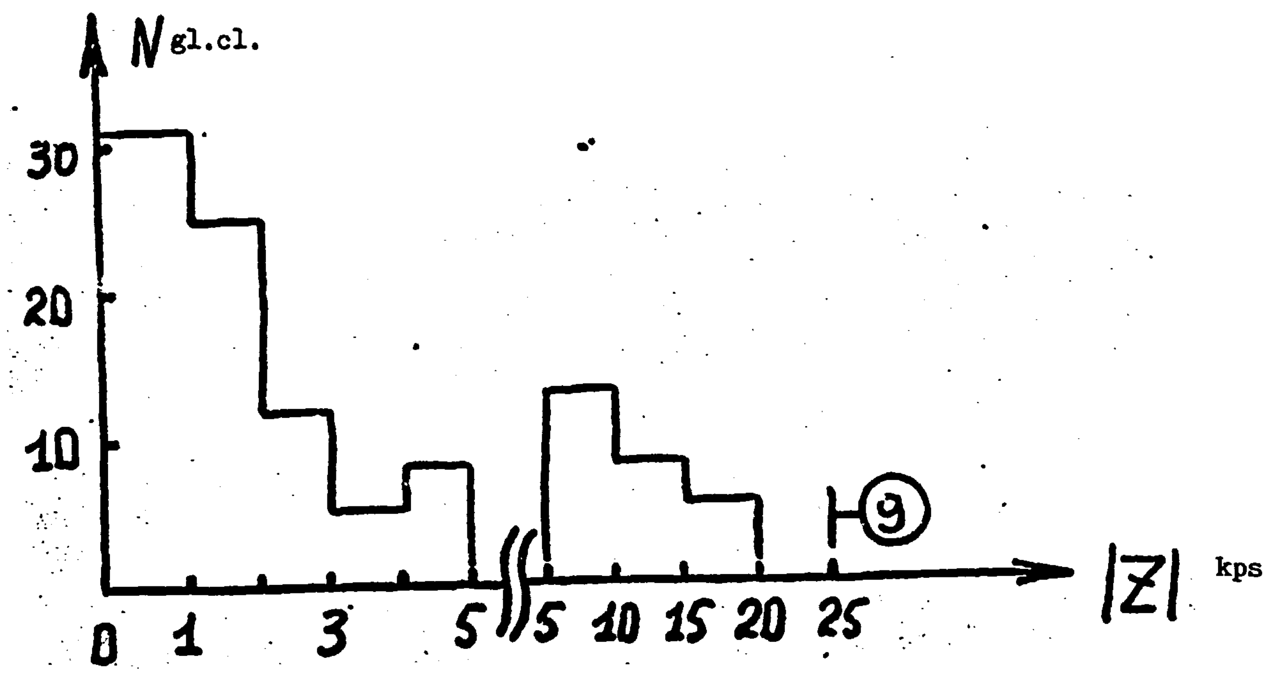

Figure 4. (continued from previous page).

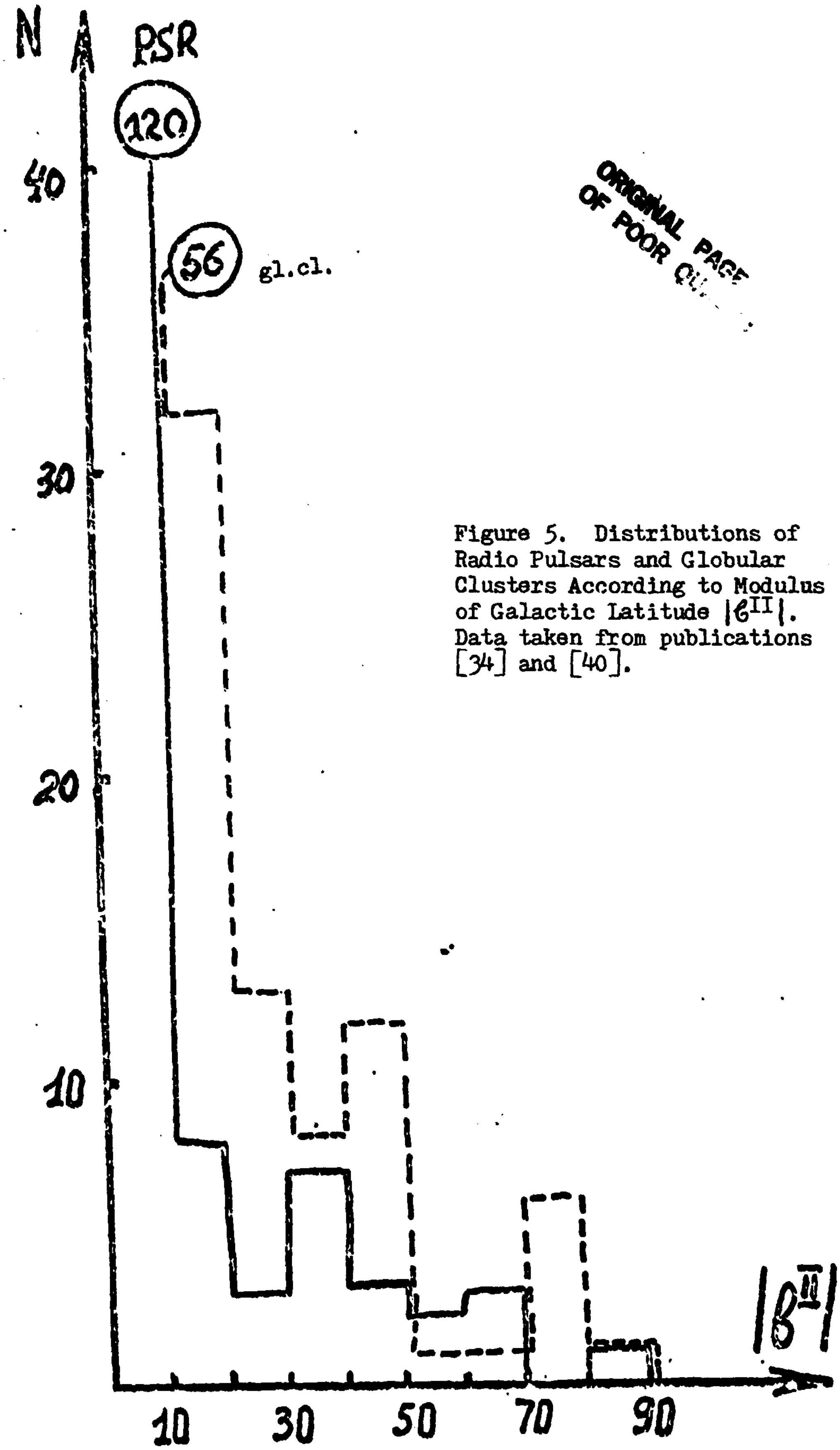

Figure 5. Distributions of Radio Pulsars and Globular Clusters According to Modulus of Galactic Latitude $|б^{II}|$. Data taken from publications [34] and [40].

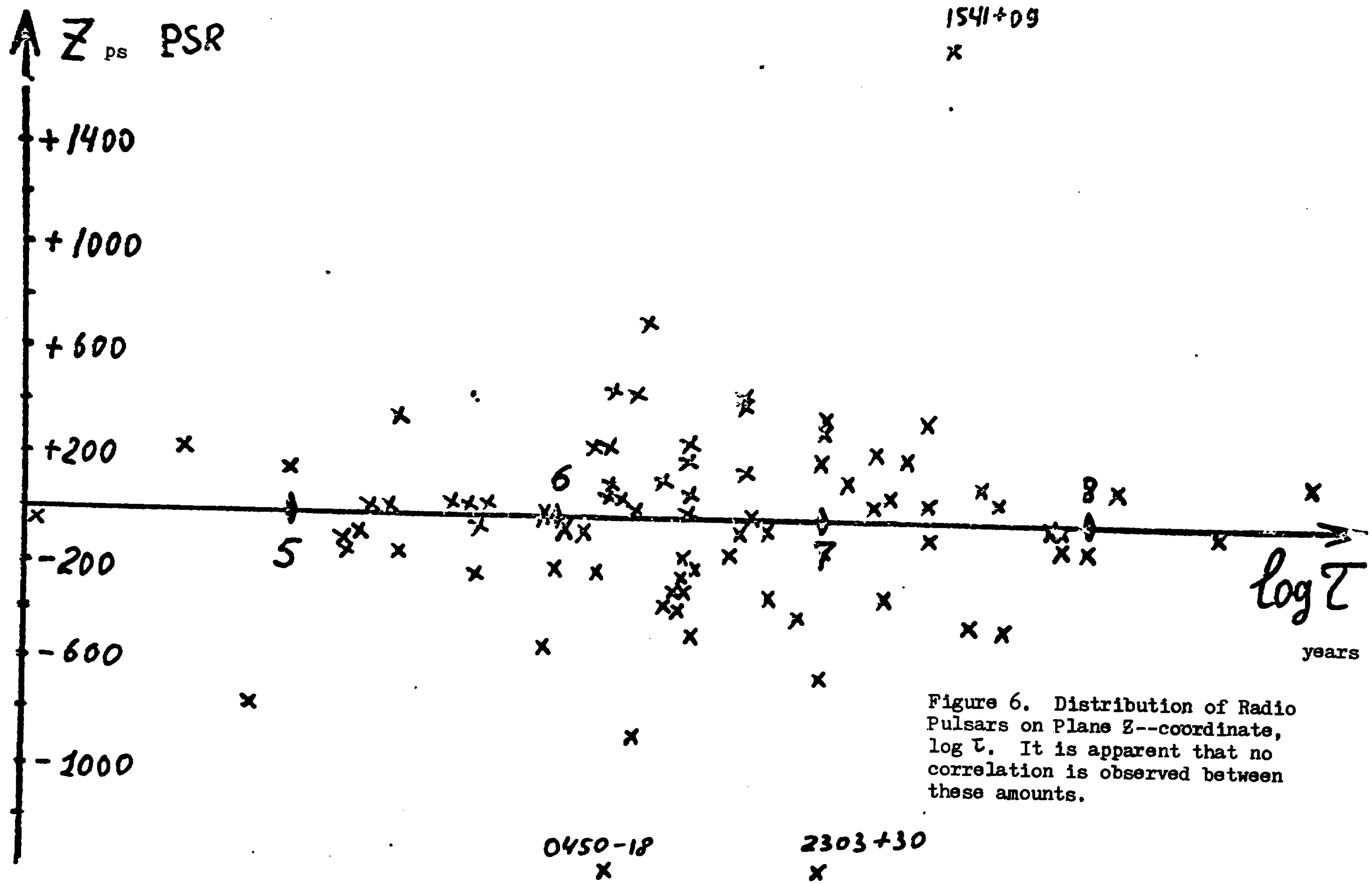

Figure 6. Distribution of Radio Pulsars on Plane Z--coordinate, log τ. It is apparent that no correlation is observed between these amounts.

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