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A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences was held on 25 March 1994 in the P L Kapitsa Institute of Physics Problems. The following reports were presented at the session:

(1) **I D Karachentsev** "Hidden mass in the local system of galaxies";

(2) **V G Klochkova, V E Panchuk** "Lithium and beryllium in the problem of cosmic-matter evolution";

(3) **G A Stepanyan** "The second Byurakan survey";

(4) **Yu Yu Balega** "10 years of interferometry on the 6 m telescope";

(5) **G M Beskin, S N Mitronova, S I Neizvestnyi, V L Plokhotnichenko, M Yu Popova** "Investigations of relativistic and rapidly varying objects with high temporal resolution";

(6) **T V Shabanova** "Discovery of a planetary system around PSR 0329 + 54."

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Lithium and beryllium in the problem of cosmic-matter evolution

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The elements Li, Be, and B play a special role in the formation of our understanding of the Universe. They are exhausted in stellar interiors, and are not replenished by ordinary nucleosynthesis processes. These elements are formed very slowly owing to the Coulomb repulsion of the nuclei of helium isotopes and to the low concentration of ^{3}He nuclei, but are burnt out quickly in the hydrogen medium. This is why observation of an abundance of these elements in stellar atmospheres is evidence either for the existence of Li and Be in the protostellar matter and low efficiency of mixing processes that dilute stellar atmospheres with matter rich in the burnt-out nuclei of Li and Be, or for the existence of processes synthesising these elements with subsequent fast transfer into layers where reactions with protons are no longer effective. The Li and Be abundance has been found to be higher in cosmic rays than in stellar matter, and this is the foundation for the model of their synthesis in spallation reactions on the CNO nuclei. The complex interrelation and poor theoretical understanding of the different ways in which the synthesis and destruction of the light elements occurs does not permit one to construct a quantitative picture of the evolution of these elements, consistent with other aspects of galactic evolution. The lines of these elements fall into different spectral ranges (Li I λ6707 Å, Be II λ3130 Å), and the rate of acquisition of observational data is fully determined by the development of ground-based and extra-atmospheric spectroscopy techniques. The requirements of a high spectral resolution and a low signal-to-noise ratio in the majority of tasks make large telescopes the instruments of choice for these studies.

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In the complex problem of Li and Be evolution one can define the following major tasks.

(a) Destruction of Li nuclei in the transition from F-stars to low-mass G-dwarfs with convective envelopes. The presence of diminishing abundances of Li in the atmospheres of main-sequence stars on gradual transition to cooler stars is well known and has been studied by photographic spectra. Corresponding to these measurements, a model of Li exhaustion, caused by mixing of the envelope matter, has been constructed. Use of low-noise solid state photoreceivers revealed a 100-fold decrease of Li abundance as one moves from the GIV to the KIV spectral class; that is, the drop of the intensity of the Li line proved to be much steeper than that which would follow from the photographical observations, and it was necessary to introduce an additional mechanism for Li exhaustion in the course of the pre-main-sequence evolution.

(b) Diffusion of Li and Be ions along the envelope radius. After the advent of CCD arrays sensitive in the ultraviolet spectral range it became possible to investigate thoroughly the Li and Be abundances, and to compare them with the abundances of other elements. Had it been found that the investigated F-dwarfs with Be deficit have also a surplus of Na and Si together with a deficit of Mg, Ca, and Se, then in analogy with Am- and Fm-stars, the exhaustion of the light elements Li and Be in outer atmospheric layers could have been explained by processes of diffusion separation of elements. However, such peculiarities in the chemical composition of stars with normal and low Be abundance have not been discovered. Thus, low Be and Li content is determined not by the diffusion process, but rather by processes of global mixing which decrease the content of easily disrupted nuclei but keep constant the content of other elements.

(c) Mixing depth in the envelope. Dwarfs from the galactic disc with a Be deficit have been found to have a large Li deficit as well. Cases of unchanged primordial Li content and Be deficit are unknown. Nuclei of Be are effectively destroyed at a higher temperature (3.5×10^6 K) than Li nuclei (2.5×10^6 K). Some cases are known in which the Li content decreased, whereas the Be abundance remained primordial; that is, in these cases the mixing extends to layers where Li burns out effectively, and Be does not. The rate of burning out of ^{6}Li is two orders of magnitude higher than that of ^{7}Li. Thus, there is a strong possibility of studying processes of lithium destruction on shorter time scales, or under a less effective mixing in the envelopes.

(d) Change of Li content with the age and mass of the star. This problem is being solved by spectroscopic observations of stars in open clusters of different ages. In the transition to older disc clusters, one observes a shift of the low-temperature drop $N_{\mathrm{Li}}(T_{\mathrm{e}})$ toward regions of hotter stars. In a narrow temperature interval near $T_{\mathrm{e}} = 6600$ K a dip in the concentration N_{Li} is discovered in several open clusters. The existence of the dip and its depth depends on the age of the cluster; the dip is not formed at stages earlier than the main sequence. To explain the dip a diffusion mechanism was proposed, which is less effective at the low-temperature part of the $N_{\mathrm{Li}}(T_{\mathrm{e}})$ curve because of mixing. At the high-temperature part of the $N_{\mathrm{Li}}(T_{\mathrm{e}})$ curve the diffusion mechanism has no time to create a significant Li deficit in the stellar atmosphere during the lifetime of the cluster.

(e) Change of Li content change with the age of the protostellar matter. The complex picture of the dependence of Li content on the temperature of the star strongly restricts the number of cluster members whose spectra permit the determination of the protostellar content of Li. Stars located between the turn-off point and the Li dip were used to establish the dependence of the Li content in the protostellar matter on the age of the investigated cluster. It would appear that, in the galactic disc, synthesis of Li takes place; this Li part does not get destroyed in the stellar state and reaches the interstellar medium from which younger stars are formed.

(f) Synthesis of Li and Be nudei after formation of the galactic disc. Owing to the destruction of Li and Be nuclei by protons, special conditions are needed for the fast transportation of these nuclei from the zone of synthesis. The creation of light elements is possible at the front of a strong shock wave moving in the envelope of a supernova. Light elements are formed in the course of spallation of heavy nuclei when the particle energy exceeds 2 MeV per nucleon inside the ion heating zone at the shock wave front. A substantial amount of ^{7}Li and ^{11}B isotopes is formed at the shock wave front, but only the ^{7}Li isotope is formed in the case of chemical abundances typical of Population II stars. The most interesting possibility is ^{7}Li synthesis during explosions in novae. Observations indicate a significant enrichment of matter expelled by novae in C, N, O, and Ne, whereas models of fast novae with an initial solar ^{3}He content give ^{7}Li enrichment by more than 100 times. However, to explain the observed galactic ^{7}Li content requires either a strong increase in the rate of novae explosions, or a 10-fold increase in ^{3}He abundance, neither of which is confirmed by observations of the interstellar matter.

(g) Role of spallation reactions on galactic cosmic rays. The sequence of cross sections of spallation reactions by protons and α-particles on C, N, and O nuclei follows (with the exception of ^{7}Li) the sequence of concentrations of isotopes of Li, Be, and B. The time needed for the creation of the observed concentration of Be in the disc is comparable with the lifetime of the Galaxy. These considerations underlie a model of the formation of Li, Be, and B nuclei in the spallation reactions of galactic cosmic rays (GCR). An important element of the model is the assumption of constancy of both the GCR flux and the spectrum on timescales of 10^{10} years. An observational test of the model is provided by the study of the $^6\mathrm{Li}/^7\mathrm{Li}$ isotopic ratio. This requires use of the limiting spectral resolution ($R > 10^5$). Studies of the atmospheres of bright dwarfs and subdwarfs, as well as inter-stellar matter spectroscopy, showed that $^6\mathrm{Li}/^7\mathrm{Li} < 0.1$, whereas the spallation model gives $^6\mathrm{Li}/^7\mathrm{Li} = 0.5$. Therefore, we must look for other reasons to explain ^{7}Li formation. With the increasing number of measurements of Be content in the atmospheres of the oldest galactic stars, new questions have arisen. First, the Be content depends linearly on the oxygen content, whereas the model of Be production by the spallation reactions on GCR gives a quadratic dependence. Second, the observed ratio is $N_{\mathrm{B}}/N_{\mathrm{Be}} = 5$, which is in contrast to the $N_{\mathrm{B}}/N_{\mathrm{Be}} = 15$ given by the spallation model. Third, if one adopts the GCR production of Be, then the observed ^{7}Li/Be ratio does not match the theoretical one, $N_{\mathrm{Li}}/N_{\mathrm{Be}} = 10^{-[\mathrm{Fe/H}]}$. Thus some doubts are cast on the classical model of the synthesis of light nuclei by GCRs. A weak point of the model is the assumption that the spectrum of GCRs at the time of formation of the Galaxy is the same as that observed at present. The model can be still made to work if one increases the proportion of high-energy GCRs ($E > 200$ MeV) in the early Galaxy.

(h) Estimates of relic lithium content. A diversity of Li contents in stellar atmospheres is observed in the galactic disc. For the older population of the halo with $[\mathrm{Fe/H}] < -1.5$, a constant value of Li abundance is typical. Stars with temperatures less than 5500 K are an exception, because in these stars Li is destroyed during the billions of years of the subdwarf's lifetime through mixing of the envelope with layers where the pp-cycle occurs. There are two ways of estimating the primordial Li concentration. First, one can adopt as a cosmological value the atmospheric Li content observed in subdwarfs, $N_{\mathrm{Li}} = 1.2 \times 10^{-10} N_{\mathrm{H}}$. The density of baryons in the standard homogeneous model obtained with this value, coincides with the densities determined from deuterium and helium. All these densities are too small to close the Universe by nucleons. Second, one can accept as a lower limit to the cosmological value the atmospheric Li content in young dwarfs from the galactic disc, $N_{\mathrm{Li}} = 10^{-9} N_{\mathrm{H}}$, and then suppose that the greater part of Li is already destroyed in older objects. This idea is further supported by the fact that the mechanisms of Li destruction and its removal from the atmosphere are well worked out; however, no effective ways of Li content enhancement by an order of magnitude in the transition from halo to disc are known.

(i) Problem of determination of the relic Be content. Li nuclei are destroyed faster than Be nuclei. The independence of Li content from the age of subdwarfs may imply that there was not enough time for a substantial amount of the Li nuclei to be destroyed. Then, Be nuclei in the same atmospheres would also not have been destroyed; that is, there is in principle a possibility that the protostellar, primordial Be abundance could be measured. The first estimate of Be content in subdwarf atmospheres was made by means of IUE observations and is $N_{\rm Be} < 3 \times 10^{-12} N_{\rm H}$. After an echelle-spectrograph with a two-dimensional photon counter had been attached to the Coude focus of the AAT telescope, the first ground-based high-precision observations of the Be II line $\lambda 3130$ A were made. In contrast to the Li case, the Be content at low metallicities did not to flatten out, but instead decreased monotonically as the metallicity decreased (age increased) to a minimal value $N_{\rm Be} = 10^{-13} N_{\rm H}$. The abundance of Be calculated in the framework of a standard homogeneous model of the Big Bang is $N_{\rm Be} = 10^{-18} N_{\rm H}$ and is much below current observational capabilities.

(j) Primordial nucleosynthesis with inhomogeneous density distribution. Observational data on the primordial abundance of the light elements ^{2}H, ^{3}He, ^{4}He, ^{7}Li are in good agreement with the predictions of the standard Big Bang nucleosynthesis model. One of the basic assumptions of the standard model is a homogeneous matter distribution. If one admits the existence of density fluctuations in the very early Universe, additional nucleosynthesis is possible in high-density regions because of unequal diffusion of protons and neutrons. A Be content three orders of magnitude higher than that given by the standard Big Bang model is predicted. When allowance is made for the reverse diffusion of neutrons into regions rich in protons, the aforementioned discrepancy in Be abundance between homogeneous and inhomogeneous models diminishes. In analogy with the Li plateau, which probably indicates a cosmological Li content, when metallicity reaches some minimum value a Be plateau should set in; this allows us to measure the cosmological content of Be. That is why observing the resonance doublet Be II $\lambda 3130$ Å in the spectra of subdwarfs is now one of the most important spectroscopic tasks relating to the problem of primordial density fluctuations.

As key observational programmes we consider: (i) measuring the isotope ^{6}Li/^{7}Li ratio in stars and in interstellar matter, (ii) precisely determining the average value of ^{7}Li content in the atmospheres of the oldest halo stars, and (iii) large-scale determinations of Be content in subdwarf atmospheres.

The main characteristics of the spectral facilities of the first generation (spectral resolution, efficiency of light receivers, spectral range) with which the 6 m telescope has been equipped in the second half of the seventies do not satisfy any of the requirements for the listed key programmes to be successfully carried out. A new complex of high-resolution spectral facilities fitted with domestic CCD arrays has been developed, manufactured, and used in the Special Astrophysical Observatory of the Russian Academy of Sciences in 1989–1992. It contains:

(1) An echelle spectrometer in the Coude focus of the 1 m telescope (maximum spectral resolution $R = 1.5 \times 10^5$). It is used for the determination of the ^{6}Li/^{7}Li isotope ratio in the atmospheres of bright stars and in the interstellar medium.

(2) An echelle spectrometer in the Nasmith focus of the 6 m telescope ($R = 2.5 \times 10^{14}$). It is used for large-scale measurements of the Li content in atmospheres of the oldest nonevolved stars in the Galaxy. A number of old halo stars was studied, which made it possible to reduce the error in determination of the primordial ^{7}Li content. In addition to the Li content, we used the method of atmosphere models for determining the content of a further 20 chemical elements synthesised by fundamentally different processes.

In contrast to the observations of the resonance doublet Li I $\lambda 6707$ Å, observations of the resonance doublet Be II $\lambda 3130$ Å are very difficult. First, subdwarfs are less luminous in this spectral range than in the red band; second, ozone absorption is of the order of one-and-a-half magnitudes here; third, there is the problem of having an adequate light receiver (one needs a CCD sensitive in the ultraviolet); fourth, the spectrometer must have a good ultraviolet transparency (all fast spectrometers have, as a rule, been designed for the range $\lambda > 3300 - 3600$ Å). To override these difficulties, we designed and manufactured an echelle spectrometer for the primary focus of the 6 m telescope ($R = 5 \times 10^4$). The device is intended for studies of Be abundance in the atmospheres of subdwarfs, as well as for determination of the Li content of stars and of the interstellar matter.

All the above spectrometers can be used for solving many other spectroscopic problems.

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Investigations of relativistic and rapidly varying objects with high temporal resolution

G M Beskin, S N Mitronova, S I Neizvestnyi, V L Plokhotnichenko, M Yu Popova

1. Introduction

A major programme searching for and studying the variability of diverse types of astrophysical objects on time scales ranging from 10^{-7} to 10^{2} s, called the 'MANIYa experiment' (multichannel analysis of nano-second brightness variability), has been pursued by the Special Astrophysical Observatory of the Russian Academy of Sciences since 1972.

Brightness variations of this kind are caused by non-stationary energy-transformation processes occurring in the strong gravitational and/or magnetic field of neutron stars and black holes (single or in binary systems), in white dwarfs, and in active regions on the surface of flare stars. High-temporal-resolution observations of these objects permit one to draw conclusions about their physical properties, as well as about their interaction with accreting plasma. Photometry with 10^{-7} s temporal resolution serves as the main tool. The observations are being made in two spectral UBVR-bands synchronously (in only one band prior to 1992) by means of a photon-counting photometer attached to one of the foci of the 6 m telescope, a 'time-code' converter ('Kvantokhron'), and an AT-386 PC. The equipment allows one to measure the arrival times of individual photons with an accuracy of ± 20 ns; series of such events are then analysed by different statistical methods. The equipment and data-processing methods are described in Refs [1–3].

It should be emphasised that the original concept of the experiment was elaborated by V F Shvartsman [4]; he directed the construction of the equipment and the development of algorithms for periodicity searches. Since his death in 1987, collaborators of the group founded by him have continued studies according to his programme.

Some results of the quest for and studies of relativistic and rapidly varying objects, which were made with the high-temporal-resolution 6 m telescope, are presented below.

2. The search for single stellar-mass black holes

In 1971 Shvartsman showed that a luminous aureole produced by an accreting gas must be formed around a single black hole of stellar mass [5]. No lines are visible in the spectrum of the aureole, with the maximum energy output falling into the optical spectral range. The intensity of the radiation of the plasma accreting onto the black hole must change on a characteristic time scale of $\tau \sim r_g/c \sim 10^{-5}$ s. The last property is a critical feature for the identification of an object as a black hole.

Around 200 objects without lines in their spectra were selected. Some of them lie close to the Sun (< 200 pc) and are now identified as high-proper-motion DC-dwarfs. Another type of black-hole candidates, the so-called ROCOSs, are star-like radio sources with continuum optical spectra.

A total of 20 DC-dwarfs and 20 ROCOSs were studied in 1980–1987. In no cases was the $10^{-6} - 10^{2}$ s variability detected [6,7].

Lack of black holes among the observed 20 DC-dwarfs yields an upper limit of the proportion of black holes relative to ordinary stars in the vicinity of the Sun of 5×10^{-4}. This value is close to the proportion of stars with masses higher than $30 M_{\odot}$.

3. Studies of pulsars

3.1 Analysis of the Crab pulsar light curve

A series of observations of the pulsar PSR 0532 + 21 in the R-band were performed in 1986. About 2 million photons from the pulsar were detected. Use of a stabilised reference signal, after convolution of the data with topocentric period determined by this signal, permitted us to obtain the light curve with a resolution of 3.3 μs [8]. The top of the main pulse is flat; its duration at a 90% level is 230 μs (Fig. 1). The main pulse shows no fine structure, the upper limit for its relative amplitude being 10% at 3.3 μs. On the other hand, the amplitudes of sporadic spikes with durations ranging from 5×10^{-7} to 6×10^{-5} s do not exceed 6% and

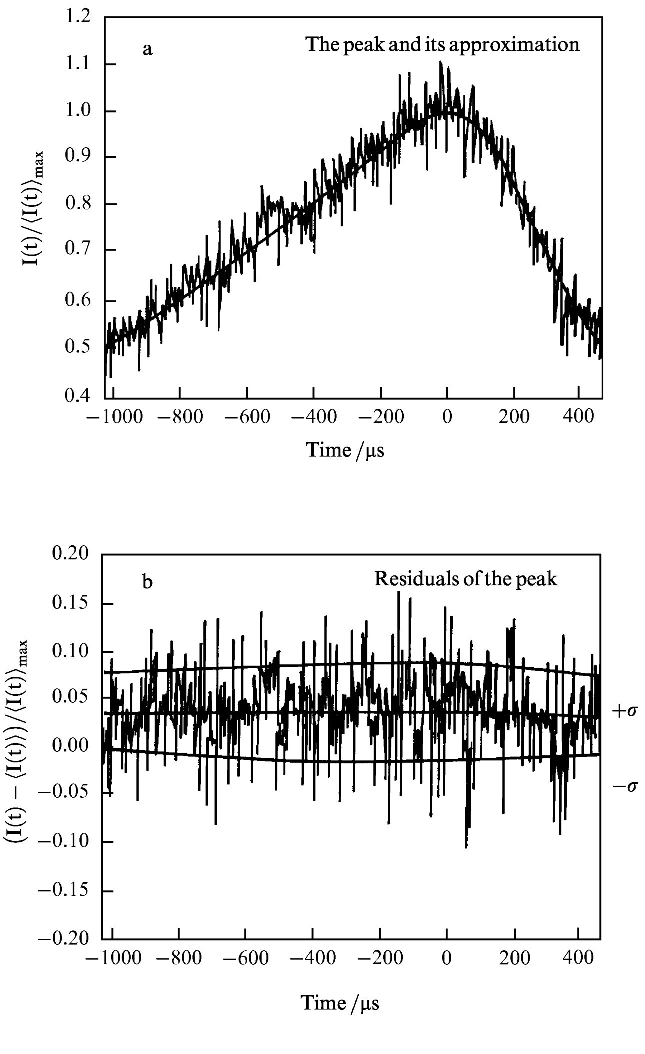

Figure 1. (a) Top of light curve of the PSR 0532 + 21 with resolution of 3.3 μs. (b) Normalised residuals between the light curve and its approximation by splines.

18%, respectively. Therefore, the characteristics of particles and magnetic fields in the zone where optical emission is generated are very stable and homogeneous.

3.2 The search for optical emission from millisecond pulsars

We studied the first millisecond pulsar, PSR 1937 + 21, with a period of 1.56 ms, and a binary millisecond pulsar, PSR 1953 + 29, with a period of 6.1 ms. Observations were made in white light with the use of 4.5 in and 7 in diaphragms. The diaphragms were aimed by means of the radio coordinates of the objects, several million photons having been collected from each pulsar. Periods were searched for with the help of a special program making use of the precalculated topocentric values. Around 500 trial periods were used. After convolution of the data, no significant deviations from the Poisson dispersion were obtained. Therefore, the optical magnitude of neither pulsar exceeds 26.5 – 27 [9].

4. Studies of flare stars of UV Ceti type

In 1983–1986 several observational runs of red dwarfs UV Ceti, CN Leo, Wolf 424, and V577 Mon were performed. In total, more than 100 flashes were detected with temporal resolution 5×10^{-7} s. Statistical analysis of the data showed that the duration of the forward front of 90% of the flashes is less than 10 s; in four cases the brightness increased over 0.3 – 0.8 s (Fig. 2); the duration of the light-curve features at the maximum and at the decline of intensity is known to exceed 0.5 s; in all the flashes no fine structure on time scales $10^{-6} - 10^{-1}$ s was detected. The minimal durations of the forward fronts of the flashes agree well with estimates derived from a thermal gasdynamic model [10]. All our results confirm the thermal nature of flashes on red-dwarf stars.

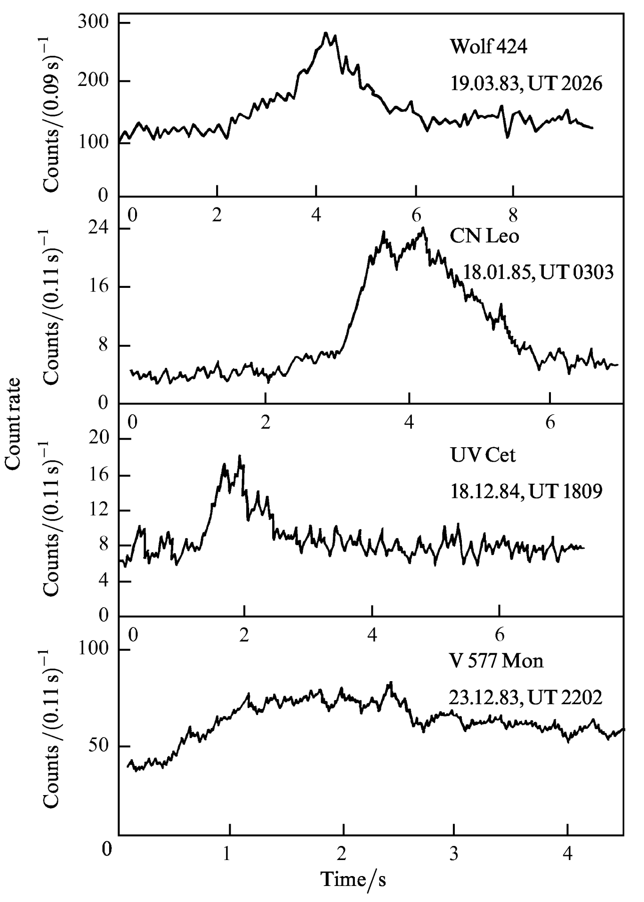

Figure 2. Light curves of bursts with leading front duration less than 1 s.

5. Studies of low-mass x-ray binaries

The observational appearance of accreting plasma is most pronounced in this class of objects ('illumination' due to the normal star is low). Since 1983 we have observed approximately 10 such systems, and the studies continue. The most interesting results were obtained for two x-ray Novae, A0620-00 (Nova Mon 1975) and GRO J0422 + 32 (Nova Per 1992) [11, 12].

Several flashes with durations of 0.5 – 5 ms and forward front durations of 0.1 – 1 ms were detected for the first object (Fig. 3). Taking into account that A06200-00 lies at a distance of 1 kpc from the Sun and that its magnitude is about 18, one can easily obtain a lower limit for the brightness temperature in the generation zone of the flashes of the order $10^8 - 10^{10}$ K. Thus, the detected flashes have a nonthermal origin.

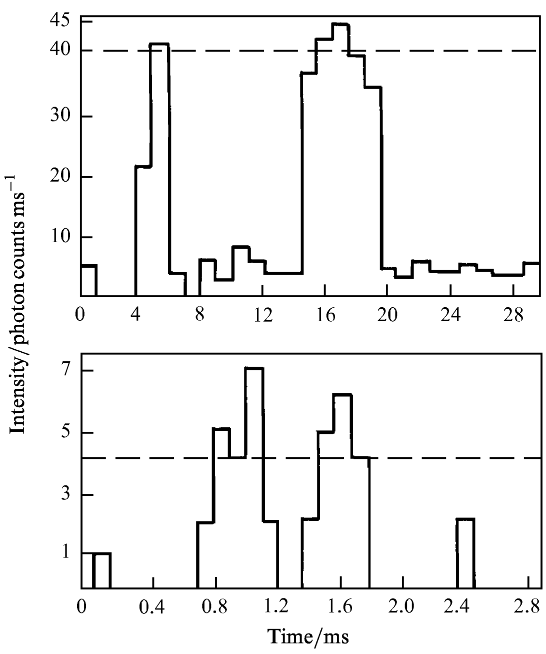

Figure 3. Ultrashort bursts of A0620-00.

GRO J0422 + 32 was observed at different phases, when its brightness decreased from about magnitude 14, soon after the maximum, to magnitude 18 near the minimum, spanning over 2 years (1992 – 1993). The object intensity at the bright phase (less than magnitude 15.5) changes on time scales of $10^{-2} - 10^{2}$ s with amplitudes of magnitude 1 – 2. Note that the fluctuations show a stochastic character without regular components. Brightness temperatures corresponding to the shortest flashes exceed 10^8 K (for distances > 2 kpc), which implies that we are dealing with nonthermal processes.

The results of observations of A0620-00 and GRO J0422 + 32 provide evidence for deviations, in some cases, from a classical disc model. Moreover, in the case of GRO J0422 + 32 we seem to observe a fragmented accretion structure.

6. Conclusions

Future advances in the study of astrophysical sources with high temporal resolution depend in many respects on the construction of a new type of coordinate-sensitive detec-tor (CSD) with high spatial (50 μm) and temporal (1 μs) resolutions. The use of such systems would permit the detection limits of fast brightness variations to be improved by magnitude 2 – 3. In other words, one would be able to detect optical pulsars with as low a brightness as magnitude 28 – 29 and to search for black holes among magnitude 20 – 21 objects.

Next in line are searches for black holes in zones with an enhanced density of interstellar matter and for pulsating emission from young supernova remnants in the nearby galaxies, synchronous multichannel observations of the Crab pulsar, and observations of optical flashes from x-ray bursters.

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Discovery of a planetary system around PSR 0329+ 54

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Planets outside the solar system are very difficult to discover owing to their weak influence on the central star position. The orbital radial velocity of a star that has a planet can be just a few cm s^{-1}. A velocity that small can be observed only by studying the orbital velocity of sources with stable pulsating periods, which radiopulsars primarily are. The presence of a planet is discovered by observing the Doppler-induced modulation of the arrival times of the pulsar signals, caused by the orbital motion of the pulsar around the common centre of mass.

More than 600 pulsars are known at present, and only around one (the millisecond pulsar PSR 1257 + 12) has a planetary system been discovered [1]. In this paper the discovery of a planet around PSR 0329 + 54 is reported. The planet has a mass of about $2M_E$ (where M_E is the mass of the Earth) and moves around the pulsar once every 16.8 years along an eccentric orbit (e= 0.2) at a distance of 7.3 AU. PSR 0329 + 54 is thus the second pulsar for which a planetary system has been discovered.

The result on the orbital motion of PSR 0329 + 54 was obtained by analysing the observations with a precise time reference. This work was performed in Pushchino from 1979 to January 1994 with the use of the BSA antenna at a frequency 102.5 MHz, and by analysing the published data of Downs and Reichley, and Downs and Krouse-Polstorff (hereafter DR and DK) obtained in 1968–1982 at a frequency of 2388 MHz [2, 3].

The Pushchino observations were made with a multi-channel radiometer (32 × 20 kHz) with a total trans-mission band of 640 kHz and time constant of 3 ms. The data acquisition interval was 2.5 ms. The mean pulse in one observation was obtained by summation (synchronous with the pulsar period) of 520 individual pulses registered as the pulsar crossed the antenna beam. The time of arrival of the pulse was measured at maximal values of the cross-correlation function calculated between the mean pulse in one observational run and a reference profile. The reference profile was derived by averaging 7300 separate pulses. The accuracy of the determination of the time of arrival was 30–100 μs.

Analysis of the times of arrival of the pulses from the PSR 0329 + 54 was performed with the use of a unified data array, which included both the data obtained at Pushchino at 102.5 MHz, and those published by DR and DK and obtained at 2388 MHz. The times of arrival of the pulses were adjusted with respect to the Solar System barycentre with the aid of the JPL DE200 ephemeris [4] and pulser coordinates [2], and then were recalculated to an infinitively large frequency to exclude the dependence of the times of arrival on the frequency of observation. The unified data array comprised 790 points distributed over a 25-year period from September 1968 to January 1994. No deter-mination of the pulsar's coordinate and proper motion was made.

The data were processed as follows. With the use of initial values of the period, P, and its derivative, $\dot{P}$, the times of arrival of the pulses were precalculated and time residuals (the differences between the observed and pre-calculated times of arrival) were estimated, which were used further to determine corrections to the initial values of the parameters. After that, the times of arrival were calculated once more, but now with the use of the corrected values of the parameters, and then the time residuals were calculated (the post-approximation residuals). The approximating polynomial had the form

$$\varphi(t) = \varphi_0 + \nu(t - t_0) + \frac{1}{2}\,\dot{\nu}(t - t_0)^2 + \frac{1}{6}\,\ddot{\nu}(t - t_0)^3 \,,$$

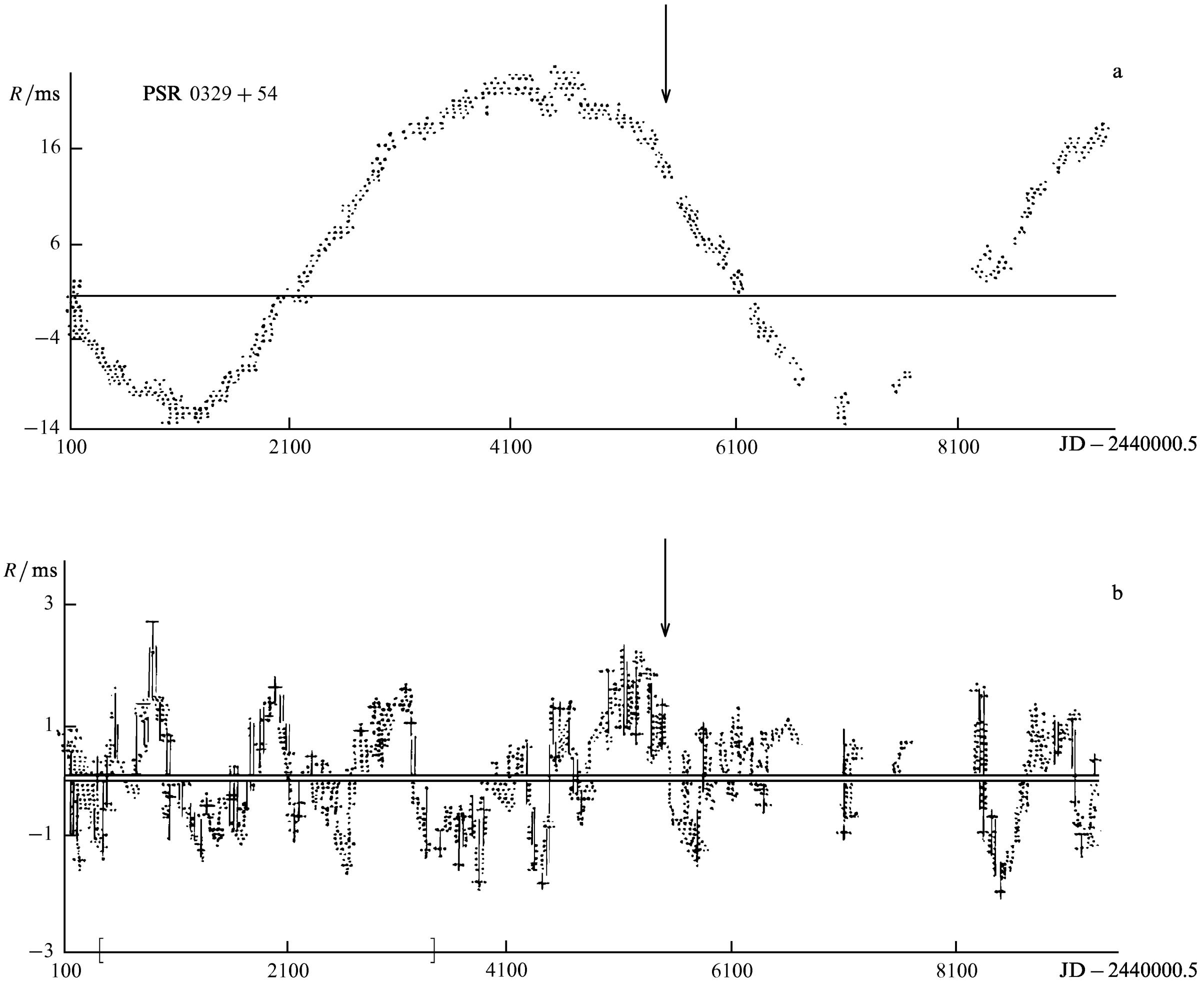

Figure 1. Time residuals of time of arrival of pulses from PSR 0329 + 54 after subtraction of (a) the polynomial with P, $\dot{P}$, $\ddot{P}$, and (b) the polynomial with P, $\dot{P}$, $\ddot{P}$, and orbital motion parameters. Time in Julian days is plotted along the x-axis, the residuals (in ms) are shown along the y-axis.

where φ_0 is the initial phase, $\nu = 1/P$ is the pulsar rotational frequency, $\dot{\nu} = -\dot{P}/P^2$ and $\ddot{\nu} = -\ddot{P}/P^2$ are its two leading derivatives, and t_0 is the time of arrival of the first pulse.

The post-approximation residuals are shown in Fig. 1a. Time measured in Julian days is plotted along the x-axis, the residuals (in ms) are shown along the y-axis. The arrow marks the meeting point of the two data arrays. The 2388 MHz DR and DK data lie to the left of the arrow, whereas the 102.5 MHz Pushchino data lie to the right of the arrow. Fig. 1a shows how smoothly one data array changes into another.

The post-approximation residuals are fitted by a sinusoidal curve and 1.5 cycles are seen over the 25-year interval of observations. The sinusoidal shape of the residuals suggest an orbital motion for the pulsar. The PSR 0329 + 54 seems not to be a single star, but has a secondary component orbiting the neutron star seen as the pulsar, and we observe Doppler modulation of the times of arrival owing to the motion of the pulser around the common barycentre of the system. The asymmetry of the residual curve implies an eccentric orbit. The parameters of the binary system orbit were obtained by adding to the barycentric times of arrival a polynomial containing the orbital parameters, in addition to P, $\dot{P}$, and $\ddot{P}$. See Refs [5–7] for a detailed discussion of the methods.

Solving the system of 9 equations by the least-squares method yielded the initial pulse phase, the rotational frequency and its two leading derivatives (φ_0, ν, $\dot{\nu}$, $\ddot{\nu}$), and the classic Keplerian elements of the orbit: the projection of the semimajor axis onto the line of sight, $a \sin i$; eccentricity, e; orbital period, P_b; periastron longitude, ω; and periastron passage time, T_0. The obtained parameters are shown in Table 1. The errors are equal to two rms errors obtained in the least-squares solution to the system of equations. Fig. 1b shows the

Table 1. Parameters of the PSR 0329 + 54 planetary system.

Pulsar period, P/s	0.714518572619 (10)
First derivative of period, $10^{15}\dot{P}$	2. 04934 (6)
Second derivative of period, $\ddot{P}/10^{-27}\mathrm{s}^{-1}$	−2. 49 (12)
Epoch/JED	2 440 105. 73037
Semimajor axis projection, $(a \sin i)$/s	0.0178 (4)
Orbital period, P_b/ e days	6140 (50)
Eccentricity, e	0.213 (16)
Periastron longitude, ω/deg	268 (3)
Periastron passage time T/ JED	2 441 011 (60)

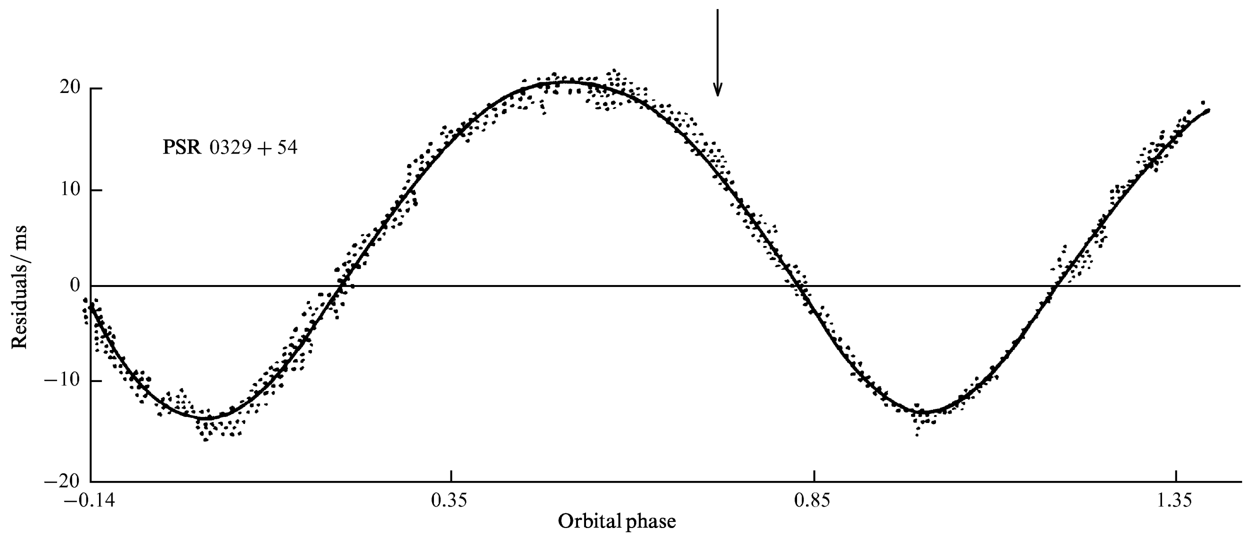

Figure 2. The solid line shows the approximation of time residuals by the calculated modulation of times of arrival by the pulsar's orbital motion with parameters from Table 1.

residuals which remained after the Doppler modulation with the found orbital parameters has been subtracted from the times of arrival. Fig. 2 shows how well the calculated orbital modulation curve (solid line) fits the observational data. Orbital phase is plotted along the x-axis.

In the post-fit residuals (Fig. 1b) one can discern a weaker modulation with an amplitude of ~ 1 ms and a much smaller period of ~ 1105 days. The modulation is clearly seen in the first part of the DR data; then the picture smears out somewhat. In the data of Pushchino 1982–1986 and 1991–1994 the modulation is not seen, probably because of equipment effects. The obtained 1105-day periodicity is not a new one. It was reported to be present in the post-fit residuals by Demianski and Proszynski [8], which they connected to the possible existence of a low-mass planet. The interval of their analysis is marked in Fig. 1b. Analysis of the DR data of Cordes and Downs [9] did not confirm this periodicity. Its existence was noted later in Ref. [10]. It is clearly seen and pronounced in the first part of the DR data presented in Fig. 1b only after subtraction of the orbital sinusoidal modulation with the 6140-day period. Should the 1105-day periodicity remain in the subsequent observations, it can be related to the orbital motion of a second planet; other interpretations, however, are not excluded.

By connecting the 6140-day periodicity with the orbital motion, one can estimate the parameters of the planetary system. The mass function corresponding to the orbital parameters from Table 1 is

$$f(m_{\mathrm{p}}) = \frac{(m_{\mathrm{c}} \sin i)^3}{(m_{\mathrm{p}} + m_{\mathrm{c}})^2} = \frac{4\pi^2}{G} \frac{(a_{\mathrm{p}} \sin i)^3}{P_{\mathrm{b}}^2},$$

$$f(m_{\mathrm{p}}) = 0.14 \times 10^{-15} M_{\odot}.$$

Here m_{p} and m_{c} are the masses of the pulsar and its companion, respectively, G is the Newtonian gravitational constant, and i is the inclination angle of the orbital plane. By adopting $m_{\mathrm{p}} = 1.4 M_{\odot}$ for the pulsar mass, one can estimate the minimal mass of the companion. The estimates have been made for the case $i = 90^{\circ}$ ($\sin i = 1$)

$$m_{\mathrm{c}} \sin i = 6.5 \times 10^{-6} M_{\odot} \approx 2 M_{\mathrm{E}},$$

that is, the companion has a planetary mass.

One can estimate the planet's semimajor axis through the use of the known orbital period and the mass of the neutron star:

$$a = \left[\frac{G(m_{\mathrm{p}} + m_{\mathrm{c}}) P_{\mathrm{b}}^2}{4\pi^2}\right]^{1/3} = 1 \times 10^{12} \text{ m},$$

$$a = 1 \times 10^9 \text{ km} = 7.3 \text{ AU} \approx 0.7 R_{♄}.$$

The size of the orbit is only slightly less than the size of Saturn's orbit around the Sun.

A question connected with the existence of a planet around a pulsar is that of the planet's survival at various stages of the pulsar's evolution, and especially during supernova explosion. The existence of planets around millisecond pulsars is easier to understand from a theoretical point of view since such pulsars are thought to have been surrounded by accretion discs, from which planets could have been formed. In the case of ordinary pulsars with 1 s periods it is especially hard to explain how the planet survives the supernova explosion. However, for the planet in the long- period 6140-day orbit with noticeable eccentricity this probability could be quite high.

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