Optical observations of nearby isolated pulsar PSR 0656+14 at the 6-meter telescope.

V.G.KURT and B.V.KOMBERG  
Astro Space Center of Russian Acad. of Sci., 117810, Moscow, Russia  
and  
V.V.SOKOLOV and S.V.ZHARYKOV  
Special Astrophysical Observatory of Russian Acad. of Sci., Karachai Cherkessia, Nizhnij Arkhyz, 357147, Russia; E-mail: sokolov@sao.ru

Abstract. The data of BVR observations of the middle-age radio pulsar PSR 0656+14 on January, 20/21 at the BTA (6-m) are presented. The brightness is determined in Cousins B filter $B \approx 25.1$ with $\lambda_{eff} = 4448 \, \AA$ in adjacent for HST F130LP long-pass filter of a star-like object, coinciding with the position of VLA radio source. Relatively large observed V and R fluxes ($\gtrsim 3\sigma$ or $> 10^{-30}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$) can witness a non-thermal nature of optical radiation of this pulsar up to $\lambda \approx 6600 \, \AA$. Most probably, in the UV-optical (BVR) spectral range a power-law spectrum is superimposed on the thermal-like radiation of the entire neutron star surface what can be related to a mechanism itself of the pulsar activity.

Key words: pulsars, ground-based observations, CCD photometry

1. Introduction

At present above 700 radio pulsars are discovered, but the optical radiation can be assumed reliably detected only for some of them: the famous Crab pulsar, PSR 0540-69, PSR 1509-58, the Vela pulsar, the gamma-ray + X-ray pulsar Geminga, and for PSR 0656+14 ((Percival, J.W., et al. 1993); (Caraveo, P.A. et al. 1994a); (Petterson, B.A., et al. 1978); (Halpern, J., and Tytler, D.: 1988); (Bignami, G.F. et al. 1996); (Caraveo, P.A. et al. 1994b); (Pavlov, G.G. et al. 1996)). I.e. the probable optical companions are already detected the which behavior can be investigated by more careful study of their spectra and temporal variability both in X-ray, gamma, radio, and optical. Recent observations at the Hubble Space Telescope (HST) in UV-optical range led to the detection of corresponding probable UV-optical counterparts of another two isolated pulsars PSR 0950+08 and PSR 1929+10 ((Pavlov G.G. et al. 1996)).

PSR 0656+14 was also identified recently in optical ((Caraveo, P.A. et. al. 1994a)) and immediately after that the study of its spectrum was started at the HST ((Pavlov G.G. et al. 1996)). At the 6-meter telescope (BTA) this pulsar and others is studied within the framework of a program of wide-band ground-based photometry of nearest pulsars of the Northern sky. For a middle-aged pulsar PSR 0656+14 ($\tau = \frac{P^3}{2} = 110000 \, yr$) we suppose to fulfill a multi-color photometry for the purpose of refinement of the nature of optical radiation of the isolated neutron star (INS), by supplementing HST UV-optical observations with ground-based BVRI-observations.

Certainly, the basic (global) goal pursued by many groups at the investigation of INSs-pulsars is to select a thermal component of radiation (including the optical one) for the pulsars of the age of $> 10^5$ years arising from the entire neutron star surface. This problem is still actual since as is noted in all recent papers on INSs
it would allow us (together with the study in EUV and X-ray ranges) to refine the thermal evolution of these compact objects and to approach in the end the correct equation of state of matter for their interior regions with supernuclear densities. A possibility is now actively discussed of a presence in the deep interior of "neutron" stars of a pion or quark condensate, a superfluidity, and others. See, for example, Umeda, Tsuruta, and Nomoto (1994); Meyer, Pavlov, and Meszaros (1994). Though, it should be remarked that UV-optical thermal radiation was apparently observed only for two active and more old pulsars: PSR 1929+10 and (probably) PSR 0950+08 ([Pavlov, G.G. et.al. 1996]). In other cases the thermal radiation from INSs is basically observed in EUV and soft X-ray bands.

The study of spectra of the nearest isolated pulsars, including the X-ray brightest PSR 0656+14, was begun with the study in X-ray ([Seward, F.D., and Wang, Z.R.: 1988]). In particular, now for PSR 0656+14 the observation in soft X-ray range of the ROSAT observatory ([Finley, J.F. et.al. 1992]) are also used. The high quality of X-ray spectra allows to determine rather precisely an effective temperature of the radiating surface of a neutron star by means of "fitting" the observed spectra to fit the black-body like radiation in Wien region. However, the most recent observations of isolated pulsars, such as Geminga and PSR 0656+14, including optical investigation ([Bignami, G.F. et.al. 1996]; [Pavlov, G.G. et.al. 1996]) showed that in optics the effects can become essential which are related either to the presence of geometrically thin (~1.5 cm), but optically thick atmosphere, or with the influence of magnetic field, or with the non-thermal contribution of radiation from polar caps, or with some other non-thermal effects. One way or another, it turns out that a simple black-body fitting an observed spectrum can be quite non-adequate to not only X-ray range ([Meyer, R.D. et.al. 1994]), but especially to optical range ([Bignami, G.F. et.al. 1996]; [Pavlov, G.G. et.al. 1996]). I.e. in the UV-optical range a non-thermal radiation could dominate the optical spectrum at least in the middle-aged pulsars.

Though the study of non-thermal radiation is interesting by itself from the point of view of elucidation of physical conditions in pulsar magnetospheres and refinement of a theory of pulsar emission, but it is nevertheless a "barrier" in the movement to the basic goal - the elucidation of the main question: "What the interior of neutron stars consist of?" On the other side, hopefully, the presence of a just non-thermal component of radiation can increase considerably the luminosity of these objects in optical. The last was also directly confirmed, in particular, by our BTA observations of PSR 0656+14 in B, V, R filters, about what the 2-d section of this paper says. We obtained for the first time the estimations of the brightness in this bands from the Earth. Though in V filter the observational material of approximately the same quality was already obtained at two ESO telescopes by (Caraveo, P.A. et.al. 1994).

The first attempt to observe PSR 0656+14 in optical was undertaken by Cordova et al. (1989) after the identification of this pulsar in X-rays. Though an optical counterpart was not then detected, this observation showed that the corresponding region around the VLA position of the pulsar is not spatially crowded and does not contain too bright objects nearer ~ 5 arcsec from the pulsar. Thereupon a successful ground-based optical observation of PSR 0656+14 which is the X-ray brightest from
all "normal" radio pulsars was fulfilled in 1989 at the 3.6-m ESO telescope for a total exposure time of 60 minutes in V filter and in 1991 with the NTT for the 70 minutes total exposure in V bandpass (Caraveo P.A. et.al. 1994a). In both cases the authors detected an object which coincides well with VLA position of PSR 0656+14 as measured by Thompson and Cordova (1994). The corresponding object has $V \sim 25$ with the error of 0.5 mag, what corresponds to the $3\sigma$ level of detection. However, a large stellar magnitude of optical counterpart together with uncertainties in the estimate of distance to the pulsar (100-700 pc) makes difficult the classification of optical both thermal and non-thermal radiation, especially in terms of uncertain interpretation of X-ray data (Finley J.P. et.al. 1992).

New observations of this pulsar were carried out at the HST with the UV-sensitive Faint Object Camera by Pavlov et al., (1996). The observations of the pulsar candidate for PSR 0656+14 were fulfilled in F130LP filter with the band width $\lambda\lambda = 2310 - 4530\AA$, with center at the 3365\AA, including the radiation in standard U and B filters. The exposure was 4755 sec. Near the VLA position of PSR 0656+14 in the deep $7\farcs4 \times 7\farcs4$ images there is only one point-like object with $m_{130LP} = 25.19 \pm 0.04$ ($S/N = 52$). Results of first observations at the 6-m telescope in more narrow spectral bands for the candidate identification for PSR 0656+14, supplementing the observations of the group of Pavlov et al. (1996) in space are presented in Section 2.

Thus, the goals of this paper are: 1). to confirm by our observations a non-thermal nature of optical radiation of the candidate identification for PSR 0656+14; 2). to understand also how the optical spectrum of this middle-age pulsar differs from an analogous spectrum of Geminga (Bignami G.F. et.al. 1996) which is much alike to it - another middle-age INS. To draw a power low spectrum Pavlov et al. (1996) used the point of $V \approx 25$ obtained in observations at NTT by Caraveo et.al. 1994) and their own point obtained at HST in F130LP filter. On the one hand, the measurements of brightness of the optical candidate identification for PSR 0656+14, which has been gained in "grond-based" B band, confirmed indeed a non-thermal nature of optical radiation of this pulsar in optical. On the other hand, $BVR$ observations at the 6-m telescope give an opportunity to say more reliably about a power-law spectrum in optical, but not about a cyclotron feature on the thermal continuum, which is the Geminga case. Section 3 describes that in more details.

The conclusion notes that in all cases of observations at the 4 telescopes and in different optical spectral bands the PSR 0656+14 turns out to be 1.5-2 stellar magnitude brighter than was expected before that on the basis of simple black-body fitting of X-ray and optical data.

## 2. The Observations.

The photometric observations of PSR 0656+14 for the purpose of detecting and estimating the brightness in $B$, $V$ and $R$ Cousins filters for PSR 0656+14 were carried out at the 6-meter telescope of SAO RAS on January, 20/21, 1996 with CCD photometer installed in the primary focus. We used CCD "Electron ISD017A" of size of $1040 \times 1160$ pixels, what corresponds to the area of $2.38 \times 2.66$ arc min in the...
Fig. 1. The $B$ field of PSR 0656+14 with the image size of $2'38 \times 2'66$. The North is top, the East is left. The cross denotes the VLA position of the pulsar. The square denotes a fragment shown in Fig.2.

sky sphere. The CCD photometer was used in such a mode ("binning $2 \times 2""), that an effective CCD size was $520 \times 580$ elements with the size of a separate element being $0.274 \times 0.274$ arc sec.

We obtained 4 exposures each 600 s in $B$ filter, 4 exposures each 600 s in $V$ filter and 4 exposure each 400 s in $R$ filter. Unfortunately, during approximately two hour of observations the atmospheric transparency was changing considerably, and the seeings were $\approx 2''$. Nevertheless, in the place of the best VLA position of PSR 0656+14, where a $V \approx 25$ object was already detected (Caraveo, P.A. et al. 1994a), approximately at the same level $\approx 3\sigma$ an object is also detectable on the sum of all exposures in each filter. In $B$ filter on the sum of all exposures a weak
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object is obviously present at the level of $\geq 3\sigma$, the brightness estimate of which is gained to be fulfilled with the precision not worse than it was done at NTT by Caraveo et. al., (1994) for $V$ band.

The standard processing of data included the subtraction of so called electronic shift - and additive component of CCD result signal - and the division into ”the flat field”, i.e. the correction of non-uniform sensitivity of detector elements. The traces of space particles were eliminated by the method of interpolation between neighbour values. Since in the moment of observation the atmospheric conditions were not photometric, the photometric calibration of the object in the area of the localization of PSR 0656+14 was carried out with the help of CCD photometric observation (in the same $BVR$ Cousins system) at the 1-meter Zeiss-1000 telescope of the SAO RAS in March 1996 in a good photometric night. Astrometric referencing of the pulsar position on the obtained CCD images was fulfilled by Digital Sky Survey (DSS), and also by optical data published by Caraveo et al.. (1994). All processing was made with the use of a software ”MIDAS”.

Figure 1 shows the image - one of 600th second exposure in $B$ filter. The field of PSR 0656+14 with the frame size of $2'38 \times 2'66$. N to the top, E to the left. The cross corresponds to the position of $V$-candidate identification for PSR 0656+14 using the two images obtained by by Caraveo et al.(1994). This position is determined by bright stars with an accuracy of a pixel size ($0'274$) in our image. The square marks a fragment of the PSR 0656+14 field, the sum image of which is shown in Fig.2. The size of the fragment is $25'' \times 25''$. Fig.2 shows a result of Gauss smoothing by a sum of four exposures in $B$ filter with the total exposure of 2400 s. A faint source with $B = 25.1 \pm 0.5$, coinciding with the VLA position of PSR 0656+14: $\alpha(1950) = 06^{h}56^{m}57.942$; $\delta(1950) = 14^{o}18'33''8$ is in the center of the fragment. Although detected only at $\approx 3\sigma$ level, its reality is not in doubt. It should be noted that the effective time of observation of the object of such a magnitude and a corresponding value of Signal/Noise ratio for a good transparency and at seeings not worse than $1''5$ is less than 10 min.

Thus, because of the bad weather conditions the photometric estimate of brightness corresponding to extra-atmospheric Log Flux ($erg\ cm^{-2}\ s^{-1}\ Hz^{-1}$) = $-(29.43 \pm 0.20)$ which we use in Section 3 for ”the joint” of ground-based $BVR$ observations and HST F130LP observations in frequency adjacent F130LP and our Cousins B filter turns out to be the most reliable only for $B$ filter. (For the Cousins $B$ filter: $\lambda_{eff} = 4448\ \text{Å}$ and $FWHM = 1008\ \text{Å}$. Since in the sum $V$-images and $R$-images ”hot pixels” are observed at the level of $\leq 3\sigma$ at the same place, now we can only say that most probably the observed object does not obey the Rayleigh-Jeans-like law in these bands also. Here the fluxes are obviously greater than the $10^{-30}\ erg\ cm^{-2}\ s^{-1}\ Hz^{-1}$.

We fulfilled the pass from the stellar magnitudes of the Cousins system to the absolute fluxes in $erg\ cm^{-2}\ s^{-1}\ Hz^{-1}$ with the use of data on $\alpha$Lyr published by Fukugita et.al. (1995).
3. Discussion.

In Fig.3 all extra-atmospheric UV-optical fluxes detected for the PSR 0656+14 candidate in different badpasses known by September 1996 are shown. The wide cross shows the energy flux detected with the F130LP filter of the UV-sensitive Faint Object Camera on-board HST. The cross labeled "$B = 25.1$" shows the result of photometric estimate of the PSR 0656+14 candidate brightness in the Cousins $B$ filter at the 6-m telescope on January, 25/26, 1996. The cross with "$V = 25$" shows the results by Caraveo et al. (1994). The line labeled "$\nu^{-0.85 + atm}$" shows a fit the UV-optical (space + ground-based) data for these 3 spectral points.

Here we give one of possible interpretations of thermal soft X-ray ROSAT and UV-optical radiation for PSR 0656+14 candidate, supposed in the paper by Pavlov et al. (1996). The curve "$\nu^{-0.85 + atm}$" is a two-component model, combining a power-law with a magnetic model atmosphere spectrum. The spectrum corresponding in the UV-optical range to only this magnetic model atmosphere is
Fig. 3. Its shows the "B-joint" of extra-atmospheric (Pavlov, G.G. et.al. 1996) and the ground-based photometric data known by September 1996. The wide cross shows the energy flux detected with the HST F130LP (B+U+...) filter, which, beside HST UV radiation, transmits also the BTA(6m) "ground based" B optical quanta. The cross labeled "B = 25.1" shows the result of a photometric estimate of the brightness of PSR 0656+14 candidate in the Cousins B filter at the 6-m (BTA) telescope of January, 25/26, 1996. The cross with "V = 25" shows the NTT result by Caraveo et al. (1994). The line labeled "ν−0.85 + atm" shows a fit the UV-optical (HST + ground-based) data for these 3 spectral points. The straight line labeled "atm" shows separately the magnetic model atmosphere thermal-like fluxes for effective temperature $T = 530000$ K at the entire neutron star surface and for $d = 280$ pc.

shown separately. It is the straight line labeled "atm". This radiation corresponds to the thermal-like flux, arising from the entire neutron star surface with atmospheric model effective temperature (observed from the infinity) $T = 530000$ K and for $d = 280$ pc. This surface thermal-like radiation seems to be observable only in EUV and in the soft X-ray ranges and the "atm" line is obtained by fitting the thermal soft X-ray ROSAT PSR 0656+14 candidate spectrum by different magnetic atmosphere models for a given distance $d$ to the source.

The magnetic field is $B = 4.7 \cdot 10^{12}$ G, $M = 1.4M_\odot$, ("true" radius)/(the radius for infinity) = 10km/13km. These are the parameters of a model from the paper by Pavlov et al., (1996; and references therein) used for the interpretation of observed spectrum of the PSR 0656+14 candidate at $d = 280(+60;−50)$ pc (Anderson, S.B et.al. 1993). Though, generally speaking, a very soft X-ray radiation in correspondence with small interstellar absorption allow a supposition of the distance to the
X-source E0656+14 to be somewhat between 100 and 600 pc ([Finley, J.P. et al. 1992]). And the estimate of distance to PSR 0656+14 by dispersion measure gives $d$ up to 760 pc ([Taylor, J.H. et al. 1993]). But nevertheless, 600-700 pc seem to be too large distances, since both a measured proper motion of the pulsar ([Taylor, J.H. et al. 1993]) and a very low X-ray absorption allow a possibility of approximately the same $d$, as in the case of Geminga object, for which the direct measurements of parallax give now the distance of $\approx 160$ pc ([Bignami, G.F. et al. 1996]).

As is seen from Fig.3, our estimate of brightness of the PSR 0656+14 optical candidate in more narrow "ground-based" $B$-band confirms once more a non-thermal character of UV-optical spectrum of this object even with such uncertainties in $B$ flux. It could be supposed that the contribution of neighbor objects in Fig.2 in the vicinity of our PSR 0656+14 optical candidate does not distort this estimate, since "the deviation" from Rayleigh-Jeans-like atmosphere model spectrum begins already in the wide HST F130LP filter (transmitting also BTA $B$ "ground-based" quanta) for the only bright ($S/N = 52$) point-like object in the Plate 1(a) from the paper of Pavlov et al., (1996). The last means that our data "joint" ground-based and HST observations, what in total allows to say reliably that in all the three cases the same object was observed.

Thus, an optical object coinciding with VLA-position turned out to be brighter indeed than was expected for purely black-body dependence Flux/Frequency in optical by BTA observations also. At the conditions under which the pulsar was observed in January 1996 it could not be detected at all if it is more than 2 st.mag. fainter indeed, as follows from Fig.3. January 1996 observations carried out at such weather conditions were meaningful either if the optical spectrum is non-thermal, or if the object is much nearer (than 600 pc) if we still deal with the black-body like radiation of the surface.

It should be said that our original goal was indeed to detect the thermal-like radiation from the neutron star surface. This non-thermal "interference", like the case of Geminga ([Bignami, G.F. et al. 1996]), remains a poor interpreted surprise ([Pavlov, G.G. et al. 1996]). Though the distance to the source seems to be less than 500 pc indeed, nevertheless the direct measurements of parallax are necessary since the exact distance increases the reliability of the temperature estimate of the entire neutron star surface, made by Pavlov’s group. The exact distance to the object allows also a better correction of the spectrum, as it can be done now for Geminga.

It should be also necessarily said that for the Geminga object, which is much alike to the PSR 0656+14, the situation in optics looks somewhat different. In our case the spectrum obeys the Pavlov’s power spectrum in Fig.3 and (together with HST F130LP observations) it does not show a sharp deficit of flux in the $B$ band in comparison to the $V$ brightness which apparently is observed for Geminga ([Bignami, G.F. et al. 1996]). (It should be noted that the statement or suggestion about the cyclotron feature for Geminga is based on the $B$ and $I$-ground-based data of Bignami et. al. (1988,1996) with the $B = 26.5 \pm 0.5$). From our January 1996 observations of PSR 0656+14 in $V$ and $R$ bands it follows that the $V$ brightness is close indeed to what Caraveo et al. (1994) give for the PSR 0656+14 optical candidate. The object is seen at the 6-m telescope in $R$ filter with the flux obviously
greater than $10^{-30}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$. The total means that this flat power spectrum of the PSR 0656+14 candidate begins in the HST UV-range and can be continued at least up to R-optical range.

### 4. Conclusions

So, from the result of observation at 4-th (3.6-m ESO, NTT, HST, BTA) telescopes in different optical spectral bands the PSR 0656+14 candidate turns out to be 1.5-2 stellar magnitude brighter than was expected earlier, proceeding from a simple black-body fit of X-ray + optical data. The radiation of PSR 0656+14 is basically non-thermal indeed in optical, though the entire neutron star surface radiation can become dominating in the far UV range. As to our $B$ estimate of brightness, together with HST F130LP and ground-based observations by Caraveo et al., (1994) in $V$ filter, the non-thermal spectrum can be approximated by one of power laws suggested in the paper by Pavlov et al., (1996). Most probably this object has no sharp decrease of flux in the more narrow (in comparison to F130LP) "ground based" $B$ band as compared to the flux in $V$ and $R$ filters, which (a dip) is apparently observed from Geminga (Bignami, G.F. et al. 1996).

To confirm or to rule out the tendency of continuation of the PSR 0656+14 optical candidate spectrum into the red range with one or another power-law and also to have reliable data for development of quantitative models of non-thermal radiation from INSs it is necessary to carry out additional $BVRI$ observations.

Further multicolor photometry would be needed. In particular, the Crab-pulsar spectrum is studied rather in details in this range and it is flat indeed with $\alpha = -0.11 \pm 0.13$ (Percival, J.W., et al. 1993), though all other features of these two pulsars are much different.

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