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Photometric study of fields of nearby pulsars with the 6 m telescope

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Abstract. Fields of Geminga, PSR B0950+08, PSR J1908+0734 and PSR J0108-1431 have been observed within the programme of optical study of nearby neutron stars carried out with the 6 m telescope. Our multicolour BV$R_c I_c$ photometry has yielded the following magnitudes of Geminga: V=$25^{m}_{.}3\pm0.4$; R_c=$25^{m}_{.}4\pm0.3$. The estimates of 3σ upper limits in B and I bands are $25^{m}_{.}4$ and $24^{m}_{.}9$, respectively. This is in agreement with the previous observations of Geminga. We suggest candidate for optical counterpart of PSR B0950+08, with $R_c = 25^{m}_{.}4 \pm 0.3$. When compared to the HST data obtained in UV its flux shows that this old pulsar can be brighter in near-IR than in near-UV. We have obtained for the first time images of the fields of PSR J1908+0734 and PSR J0108-1431. Although no optical counterparts have been detected, the magnitude upper limits obtained suggest further observations of these pulsars.

Key words: stars: pulsars – techniques: photometric

1. Introduction

In a vast list of more than 1000 radio pulsars there are but a few objects detected in other wavelengths ($\gamma-$rays, X-rays, far-UV, optical, see e.g., Ulmer, 1998; Becker & Trümper, 1999; Korpela & Bowyer, 1998; Mignani, 1998). Multiwavelength observations bring a wealth of a new information on the radiation mechanisms of pulsars which cannot be obtained in a narrow spectral band. For young ($\lesssim 10^4$ yrs) pulsars like those in the Crab and Vela nebula the emission in the all spectral ranges is mainly of non-thermal origin; it is produced by relativistic particles generated in magnetospheres of rapidly rotating neutron stars (NSs). Becoming older ($\gtrsim 10^5$ yrs), pulsars rotate slower, the non-thermal component weakens and one can observe thermal emission from the surface of cooling NSs. According to standard NS cooling models (e.g., Nomoto & Tsuruta, 1987), at this age their surface temperature is about 10^5–10^6K and the maximum of the thermal emission lies in the soft X-rays (0.1–2.4 keV) or in far-UV. Thermal emission with spectral temperatures in the above range has been detected during X-ray observations of some middle-aged radio pulsars (see, e.g., Becker & Trümper, 1997). Thermal X-ray emission was also detected from several radio silent objects identified as isolated neutron stars (INSs) (e.g., Neuhäuser & Trümper, 1999).

Simulations of INS cooling show that under certain conditions, depending on the NS mass/radius ratio, on equation of state and composition of superdense matter in interiors and in surface layers of the star (see, e.g., Yakovlev et al., 1999 for a recent review), thermal evolution of a NS may strongly deviate from the standard model. Theoretical investigations combined with comprehensive observational studies of thermal emission from radio pulsars and INSs of different ages enable one to understand which of the evolution scenarios are real. These studies are also of crucial importance for development of realistic models of NSs and deeper understanding of poorly known properties of superdense matter in their interiors.

Optical observations are an important part of the multiwavelength studies of INSs and pulsars. They allow one to constrain the parameters of the thermal emission in the Rayleigh-Jeans spectral region and investigate the properties of the nonthermal radiation in optical bands. Most pulsars and INSs, excepting the young Crab pulsar and PSR 0540-69, are faint optical objects. Thus, the multicolour photometry is the natural first step to search for the pulsar optical counterparts and to obtain information on their optical spectra. This is the main goal of the programme

Table 1: *Some characteristics of the pulsars under investigation*

Pulsar	J0633+1746	B0950+08	J0108-1134	J1908+0734
α_{2000}	$6^h33^m54\overset{s}{.}02$	$9^h53^m9\overset{s}{.}32$	$1^h8^m8\overset{s}{.}20$	$19^h8^m17\overset{s}{.}01$
δ_{2000}	$+17^o46'11\overset{''}{.}5$	$+7^o55'35\overset{''}{.}6$	$-14^o31'46''$	$+7^o34'14\overset{''}{.}36$
DM (pc cm^{-3})	2.9	2.97	1.83	11.1
d (kpc)	~ 0.16	~ 0.13	~ 0.09	~ 0.58
P (ms)	237	253	807.6	212.4
$\dot{P} \times 10^{-15}$ (s s^{-1})	11	0.229	0.82	0.825
τ (yrs)	$3.4 \cdot 10^5$	$1.74 \cdot 10^7$	$1.6 \cdot 10^8$	$4.07 \cdot 10^6$
$\log B$ (G)	12.20	11.40	12.40	11.63
$\log \dot{E}$ (erg s^{-1})	34.51	32.75	30.79	33.53

DM – dispersion measure, d – distance, P – rotational period, characteristic age $\tau = P/(2\dot{P})$, magnetic field $B = 3.2 \times 10^{19}(P\dot{P})^{1/2}$, energy loss $\dot{E} = 4\pi^2 I\dot{P}P^{-3}$, where neutron star inertia momentum I is accepted to be equal to 10^{45} g cm^2

which has been carried out at the 6 m telescope during last several years.

The programme includes deep (up to 27^m) photometry of the fields of some nearby pulsars. The most interesting results reported at present are those obtained for the middle-aged ($\sim 10^5$ yrs) pulsar PSR B0656+14 (Kurt et al., 1998; Koptsevich et al., 2000). Deep multicolour photometry observations of the pulsar field taken with the 6 m telescope yielded detection of the pulsar optical counterpart. The pulsar magnitudes in BR$_c$I$_c$-bands were estimated for the first time. The corresponding fluxes exceed the Rayleigh-Jeans extrapolation of the thermal spectrum seen in the soft X-rays and EUV.

In this paper we report photometry of four other nearby pulsars: Geminga (J0633+1746), PSR B0950+08, PSR J1908+0734 and PSR J0108-1431.

Their parameters are presented in Table 1. The data were taken from the pulsar catalogue (Taylor et al., 1995), excepting Geminga's DM (Malofeev & Malov, 1997).

Observations and data reduction are described in Section 2, Section 3 summarizes the results, and some conclusions are given in Section 4.

2. Observations and data reduction

Optical observations of the pulsar fields were carried out with the 6 m telescope BTA on March, 1997, January, 1998, on January, July and August, 1999 with a CCD detector mounted at the prime focus with the set of filters close to the Johnson-Cousins system. Different CCD detectors were used. Some of their characteristics are given in Table 2. Seeing varied from night to night between $0\overset{''}{.}9$ and $1\overset{''}{.}8$. Table 3 gives details on each observing run.

Standard data reduction, including bias subtraction, account for dark current, correction for non-uniformity of the detector sensitivity (flat-fielding), and removing of cosmic ray events, was performed making use of MIDAS procedures. To compensate fringes we used the so-called superflats, i.e. flats obtained directly from the sky by median-combining several science exposures taken during the night. The individual flat-fielded exposures were stacked together, yielding combined images of the fields under investigation.

For the photometric calibration we used Landolt's standards (1992). The absolute fluxes F_j in [erg cm^{-2}s^{-1}Hz^{-1}] were calculated using equations

$$\log F_j = -\left(0.4 M_j + M_j^0\right), \tag{1}$$

with the zero-points provided by Fukugita et al. (1995):

$$\begin{aligned} M_B^0 &= 19.396, \quad M_V^0 = 19.445, \\ M_R^0 &= 19.520, \quad M_I^0 = 19.623. \end{aligned} \tag{2}$$

Astrometric referencing of the images was performed using the coordinates of selected field stars extracted from the USNO catalogue using the ESO Skycat tool. The final accuracy was about $1''$.

Table 2: *Technical characteristics of CCD detectors*

Detector type	Size (in pixels)	Pixel size	FOV	Gain (e^-/ADU)	Readout noise
ISD017A	1060 × 1170	0.″137	2.′5 × 3.′0	2.3	8
Photometrics	1024 × 1024	0.″206	3.′5 × 3.′5	1.3	4
TK1034	1034 × 1034	0.″207	3.′6 × 3.′6	1.2	3

Table 3: *Observations of the PSR fields*

Date	Detector	Object	Filter	Total exposure, sec	Seeing
11.03.97	ISD017A	PSR J0633+1746	R_c	3×600	1.″6
12.03.97	ISD017A	PSR J0633+1746	V	600	1.″4
13.03.97	ISD017A	PSR J0633+1746	B	5×600	1.″8
19.01.99	Photometrics	PSR J0633+1746	I_c	2×300	1.″0
11.03.97	ISD017A	PSR B0950+08	R_c	3×600	1.″6
24.01.98	ISD017A	PSR B0950+08	R_c	5×600	2.″0
9.07.99	Photometrics	PSR J1908+0734	V	3×600	0.″9
9.07.99	Photometrics	PSR J1908+0734	R_c	2×600	1.″0
9.07.99	Photometrics	PSR J1908+0734	I_c	100	1.″0
10.08.99	Photometrics	PSR J1908+0734	B	4×600	1.″4
10.08.99	TK1034	PSR J0108-1134	B	3×300	1.″5
10.08.99	TK1034	PSR J0108-1134	V	2×300	1.″5
10.08.99	TK1034	PSR J0108-1134	R_c	5×300	1.″8
10.08.99	TK1034	PSR J0108-1134	I_c	5×300	1.″6

3. Results

3.1. PSR J0633+1746

The middle-aged Geminga pulsar has been already detected with the ground-based (CFHT, ESO 3.6 m, NTT) and HST telescopes in different bands and presently it is one of the well-studied pulsars in the optical domain (see, e.g., Bignami & Caraveo, 1996, Mignani et al., 1998). It has been concluded that the optical emission of Geminga seems to be thermal with a broad emission feature at 6000 Å. Jacchia et al. (1999) suggested a rough model to explain the observed excess of Geminga's emission in the V band as emission of hot ions in the strong magnetic field near the NS surface. The results of Geminga's spectroscopy (Martin et al., 1998) with tentative detection of an apparent absorption feature at 6400 Å are generally consistent with the photometry. In Fig. 1 we present our images of the Geminga field in the B, V, R_c bands taken on March, 1997 and in the I_c band on January 19, 1999. The pulsar position in the V and R images is indicated with arrow. The objects suggested to be Geminga candidates at the first observations of this field in the optical range (Halpern & Tytler, 1988) are marked with letters G and G′.

The photometry both of the pulsar optical counterpart (G″) and the mentioned field objects yields the magnitude estimates, which are presented in Table 4. The obtained Geminga flux distribution is in a good agreement with the data published so far. In Fig. 2 we present the broadband spectrum of Geminga based on all optical data available. Filled circles correspond to our results, and arrows with bars to the I and F675W upper limits. Our observations of the Geminga field in the I band were tentative and we could not get so deep images as had been done before (Bignami et al., 1996). Thus, the fading of Geminga's flux at these wavelengths is still unconfirmed.

In all the optical bands (excluding the I one) the optical fluxes exceed the Rayleigh-Jeans extrapolation of the thermal spectrum seen in the EUV and soft X-rays (dashed line in Fig. 2). Such a spectrum behaviour is similar to that of the PSR B0656+14 and probably can be also fitted by combination of both a magnetospheric and a thermal component.

3.1.1. PSR B0950+08

Like Geminga, the pulsar B0950+08 has been previously detected. The field of this pulsar was observed with the HST in the UV-optical range using the long-pass filter F130LP ($\lambda\lambda = 2310 - 4530$ÅÅ) (Pavlov et

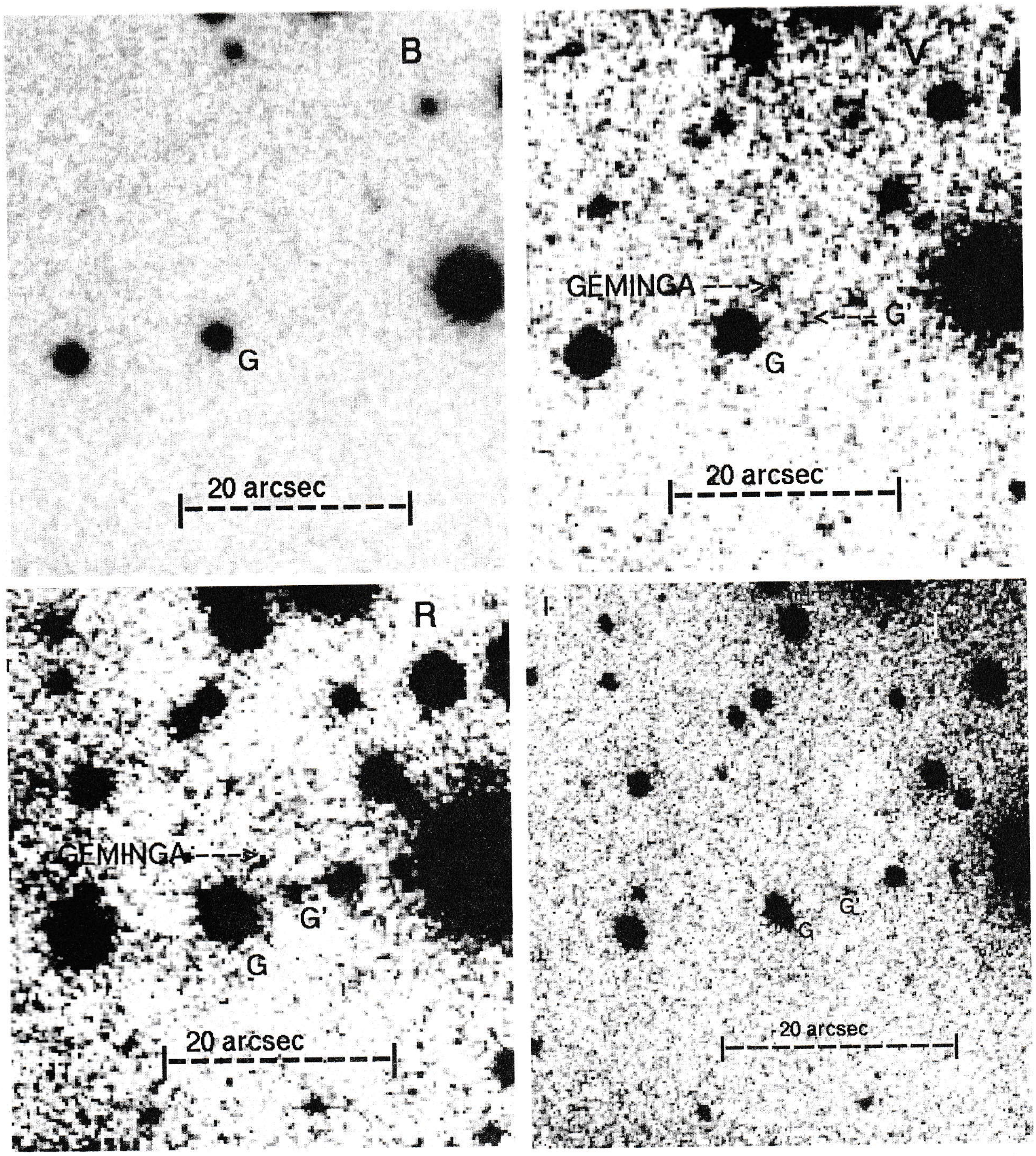

Figure 1: *The field of the pulsar Geminga (PSR J0633+1746).*

al., 1996). The flux of the only point source detected in the $7''\!.4\times7''\!.4$ FOC field of view is $F = 0.051\pm0.003$ μJy ($m_{F130LP} = 27.1$). The apparent offset of the source from the radio pulsar position, $1''\!.85$, can be associated with positional errors of the guide stars used in this observation (Pavlov et al., 1996). Meyer & Pavlov (1997) corrected the guide star positions, making use of the PPM catalogue, and recalculated the position of the putative pulsar counterpart. This correction reduced the offset to $1''\!.1$, with an uncertainty of $1''$ (Meyer & Pavlov, 1997).

The field of this pulsar was observed with the 6 m telescope in the R band of the Cousins system on March, 1997 and January, 1998. There are not enough reference stars from USNO catalogue in this field (approximately $2'\!.5\times2'\!.5$ in size), that makes an accurate astrometry impossible. To improve the situation we used the image of this field ($9'\times9'$) taken with the

Table 4: *Photometry of PSR J0633+17 (Geminga) and the nearest field objects*

	B		V		R		I	
	Magnitude	Flux[a]	Magnitude	Flux	Magnitude	Flux	Magnitude	Flux
G	22.1	5.91	20.3±0.1	27.2	20.2±0.1	25.1	19.8±0.2	28.6
G′	>25.4	<0.278	24.5±0.3	0.568	24.3±0.3	0.575	23.5±0.4	0.948
G″[b]	>25.4	<0.278	25.3±0.4	0.272	25.4±0.3	0.209	>24.9	<0.256

[a] Flux in μJy
[b] Geminga optical counterpart

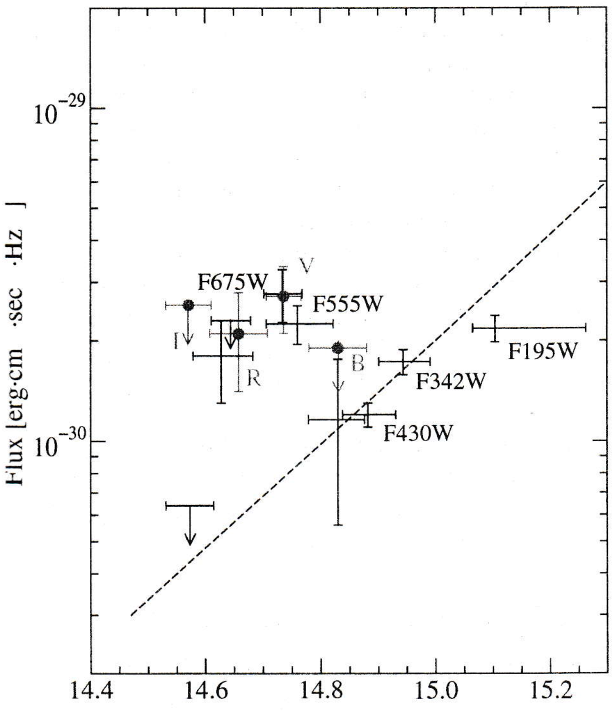

Figure 2: *Summary of available data on the multiband HST and ground-based photometry of Geminga. Data points are labeled according to the filters with which they were obtained (see text for more explanation). Dashed line shows the Rayleigh-Jeans part of the spectrum obtained at the blackbody fit of the ROSAT data of Geminga for a neutron star with the 10 km radius and the temperature of 5.77·10^5 K (Halpern, Ruderman, 1993).*

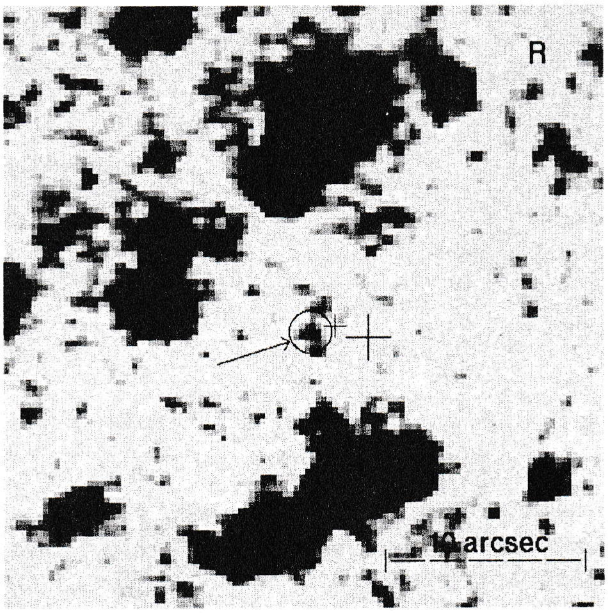

Figure 3: *The R image of the PSR B0950+08 neighbourhood; crosses indicate the pulsar radio position and the position of the HST UV-optical candidate with their uncertainties (small and big ones respectively); arrow points to our candidate to optical pulsar counterpart. The circle, which is 1″ in radius, corresponds to the accuracy of our astrometry.*

Zeiss-600 telescope of SAO RAS. This enabled us to increase the accuracy of the astrometrical referencing of the BTA images up to 1″. In Fig. 3 we present an image of PSR B0950+08 neighbourhood, positions of the radio pulsar (small cross), the UV-opical candidate (big cross) and the possible optical counterpart (in circle) are indicated. An object ($S/N = 4.2$) has been found in the combined image, and its position differs by 1.″5 from the pulsar radio position. In case the detected object is indeed the pulsar, this discrepancy may be due to two reasons: different epochs of the radio and optical observations with the lack of reliable data on the pulsar proper motion, and uncertainties both in our astrometry and the pulsar radio position. The object magnitude is $R = 25^{\mathrm{m}}.5(3)$, corresponding flux is $F_R = 0.19 \pm 0.04\mu$ Jy.

Fig. 4 shows photometric data of the possible PSR B0950+08 counterpart based on the 6 m telescope (R band) and HST (F130LP) observations.

If the observed object is the pulsar optical counterpart its R magnitude shows that old pulsars may be brighter in near-IR than in near-UV region. This is in opposite to the expected spectral behaviour and

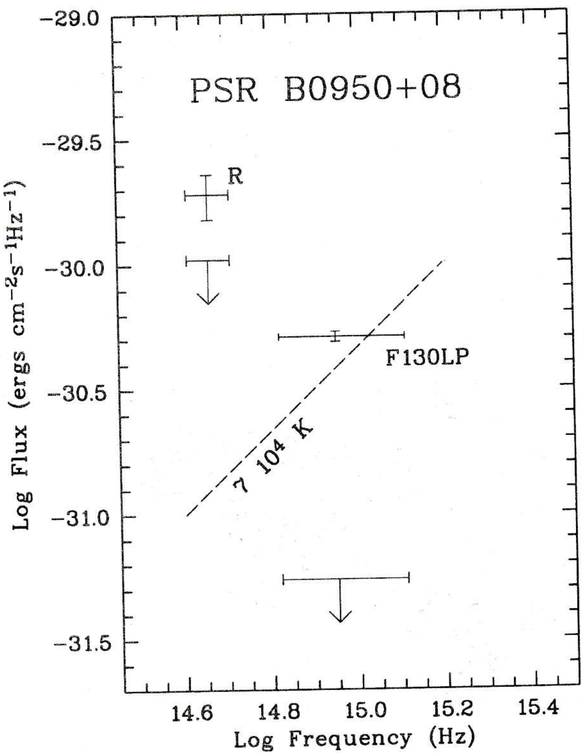

Figure 4: *Fluxes from PSR B0950+08 counterpart in the near-UV (HST) and its possible optical candidate in R (6 m telescope) ranges; arrows with bars show the corresponding 3σ upper levels on the flux of undetected sources; dashed line reflects the blackbody spectral fit for radiation from entire NS surface for the distance d = 130 pc and NS radius of 13 km (Pavlov et al., 1996).*

cannot be explained by thermal emission only. More observations are needed.

3.1.2. PSR J0108-1431

PSR J0108-1431 was discovered during a survey of the southern sky for pulsars using the Parkes 64 m radio telescope (Tauris et al., 1994). In accordance with the galactic electron distribution density model (Taylor & Cordes, 1993) the low dispersion measure suggests that this pulsar is within 90 pc from the Sun. Thus this is the closest known neutron star, but it is quite old, $\tau \sim 1.6 \cdot 10^8$yrs. The pulsar has not been detected in any high-frequency range.

Fig. 5 represents images of the PSR J0108-1431 neighbourhood taken with the 6 m telescope on August 1999. No object coinciding with the radio pulsar in position was detected and we obtained the following 3σ-limits for the observed pulsar magnitudes: B $> 25^m\!.4$; V $> 24^m\!.7$; $R_c > 25^m\!.4$; $I_c > 24^m\!.3$. Further observations of this field might yield the detection of the INS optical counterpart.

3.1.3. PSR J1908+0746

The pulsar PSR J1908+0746 was discovered at the Arecibo Observatory during the search for pulsars of low luminosity using the 305 m radio telescope (Camilo & Nice, 1995). For its characteristic age this is old pulsar, while the rotational energy loss $\dot{E}$ is rather high. In the absence of an unequivocal theory of the high-energy emission of pulsars, a high level of $\dot{E}/d^2$ is used as a rough indicator of likelihood that high-frequency emission from a pulsar can be detected (see, e.g., Goldoni & Musso, 1996). Search for the emission in the high-frequency domain from pulsars with the highest values of $\dot{E}/d^2$ (~40 pulsars including PSR J1908+0746) yielded the detection of X-rays from 27 pulsars (Becker & Trumper, 1997) and the γ-rays from 4 pulsars (Thompson et al., 1994). No high-frequency emission has been found so far from PSR J1908+0746 (Becker & Trumper, 1997).

The field of this pulsar was observed in BVR_cI_c bands on July and August, 1999. The obtained images are shown in Fig. 6. The photometry yields the following 3σ upper limits for the observed pulsar magnitudes: B $> 26^m\!.0$, V $> 26^m\!.1$, $R_c > 25^m\!.9$, $I_c > 23^m\!.4$. As this rather distant pulsar lies almost in the galactic plane, its dereddened flux values can be derived only after an accurate study of the interstellar extinction towards the pulsar position.

4. Discussion and conclusions

The deep photometric study of the PSR B0656+14 at the 6 m telescope has shown that the broadband spectrum of this middle-aged pulsar is significantly of non-thermal origin (Kurt et al., 1998; Koptsevich et al., 2000). Its complicated shape differs from flat and featureless spectra of young Crab-like pulsars and cannot be explained by a simple spectral model (Pavlov et al., 1997; Kurt et al., 1998; Koptsevich et al., 2000). Similar behaviour, confirmed by our observations, shows the spectrum of the slightly older pulsar Geminga. Some doubt still remains how deep is the fall of Geminga's flux redward of R and whether its depth is restricted by the emission level of the thermal component. More observations, including the IR-range, are needed to address this question. Nevertheless, current stage of the optical studies allows us to suggest that the optical spectra of these middle-aged NSs are likely to be very different from those of young ones and may hint the spectral evolution of the optical emission with the pulsar age.

The detection of the optical emission from the old pulsar PSR B0950+08, if proposed counterpart candidate is confirmed by further observations, may con-

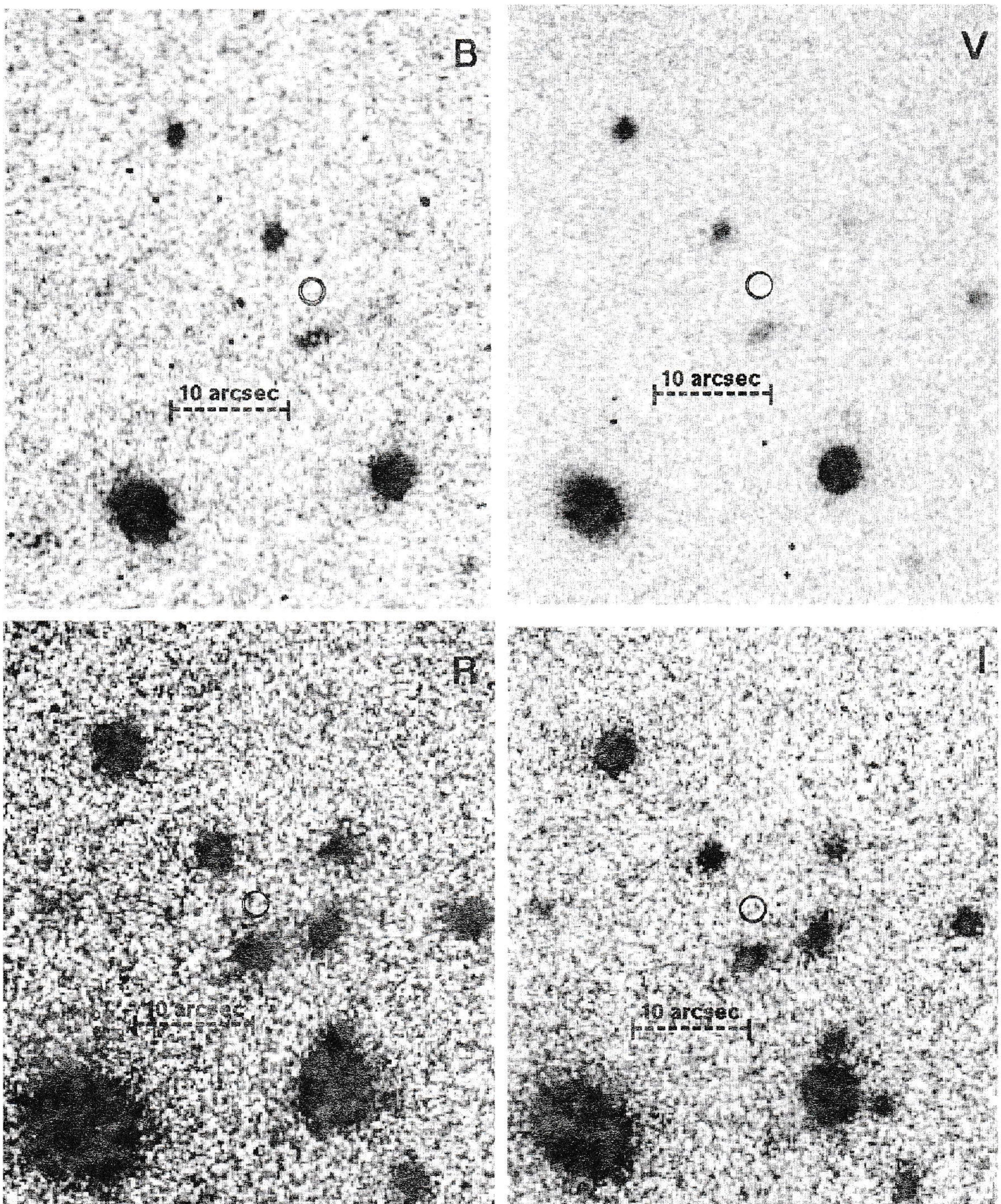

Figure 5: *The field of PSR J0108-1431, the pulsar radio position is marked with the circle, its size corresponds to uncertainties in the astrometry.*

tribute to the above idea. The apparent excess in the R band may indicate the presence of spectral feature at these wavelengths and raise a question whether thermal component is dominant in the optical emission of old neutron stars (> 10^6 yrs), which is expected from the scenario of INSs evolution. Thus, search for optical counterparts to old pulsars and cooling INSs detected in X-rays may be of great importance.

We have observed the fields of the pulsars J0108-1431 and J1908+0734 for the first time. Although no optical counterparts have been found, the estimated

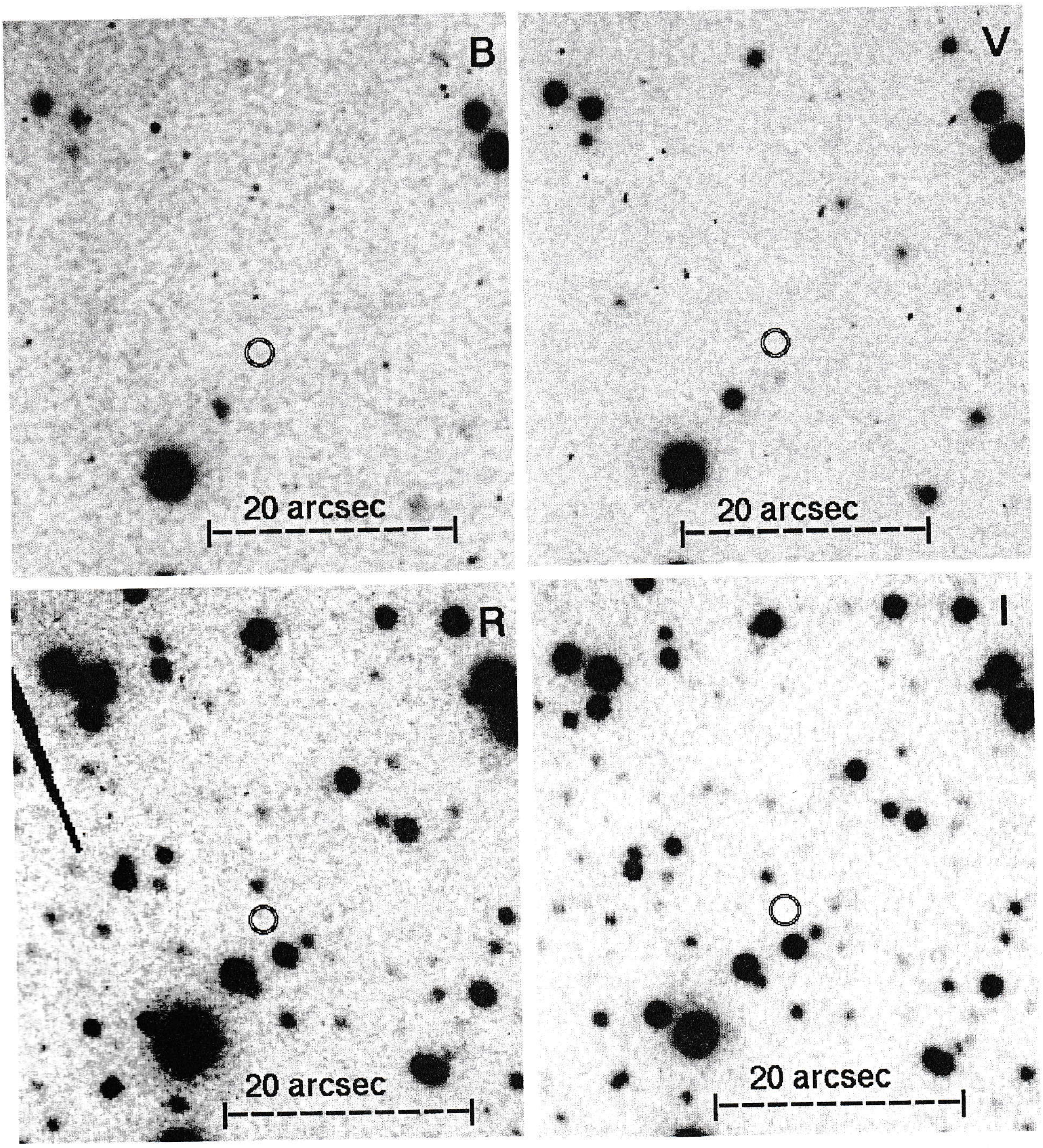

Figure 6: *The field of PSR J1908+0746; the circle marks the pulsar radio position, its size corresponds to uncertainties in astrometry.*

magnitude upper limits suggest deeper observations of the fields of these promising objects. However, the optical emission of PSR J1908+0734 seems unlikely to be detected in the B and V bands due to extinction.

The search for optical emission of more INSs with the subsequent multicolour photometric study is needed to shed light on the mechanisms of their optical emission, to put constraints to the parameters of both thermal and nonthermal components, to enrich our knowledge of the NS interior and draw a real picture of the neutron star evolution.

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