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Deep optical observations at the position of PSR1706-44 with the VLT-UT1*

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Abstract. We present optical data gathered by the *VLT* Test Camera in the V-band at the radio (interferometric) position of PSR1706-44. We find no optical counterpart to the pulsar in the *VLT* image. At a distance of $2\farcs7$ from a nearby bright star, the 3σ upper limit to the pulsar magnitude above the background is $V = 25.5$. Within an error circle of $1\farcs0$ the upper limit is degraded in the direction towards the star. At a distance $\lesssim 2''$ from the star we can with confidence only claim an upper limit of $V = 24.5$. This is still several magnitudes fainter than previous estimates. The implications of the optical upper limit taken together with the high energy pulsed gamma-ray radiation for theoretical models of pulsar emission are discussed.

Key words: pulsars: individual: PSR1706-44 – VLT – pulsars: general

1. Introduction

Optical detection of pulsars constitute a critical part of an expanding set of multiwavelength observations of isolated neutron stars that together aid in the development and constraining of theoretical models of pulsar electromagnetic radiation. To detect optical pulsations, it is necessary to unambiguously identify the optical counterpart of a pulsar that has been observed in other bands, say radio or gamma-rays. Because of its high spin-down energy loss and relative proximity to Earth, the radio pulsar PSR1706-44 has been a prime candidate for observation in many bands of the electromagnetic spectrum. (See Table 1 for a description of PSR1706-44, and a comparison with the Vela pulsar, which is of similar age.) The recent observation by the *Very Large Telescope (VLT)*-UT1 in its Science Verification (SV) phase, of the field containing this pulsar has allowed the determination of a magnitude limit in the V-band.

Table 1. Properties of PSR1706-44 and PSR0833-45 (Vela)[a]

	PSR1706-44	Vela pulsar
Distance (kpc), d	1.8^b	0.5
Pulse period, P (s)	0.1024	0.0893
$\dot{P}$ (10^{-15} s s^{-1})	93.04	124.7
log (Timing age)	4.24	4.05

[a] Data from Taylor, Manchester & Lyne (1993).
[b] Alternate $d = 2.4$ kpc (Koribalski et al. 1995; Thompson et al. 1996).

A number of rotation powered pulsars are found to emit high energy radiation (from optical to gamma-ray bands) which is a combination of differing amounts of three spectral components: 1) power-law emission, resulting from non-thermal radiation of particles accelerated in the pulsar magnetosphere, 2) soft blackbody emission from surface cooling of the neutron star, 3) a hard thermal component from heated polar caps. In addition, there is often a background of unpulsed emission from a surrounding synchrotron nebula.

PSR1706-44 belongs to the set of seven γ-ray pulsars detected by EGRET (Thompson et al. 1996). It has been detected as an unpulsed point source by ROSAT (Becker et al. 1995). While it has not yet been seen as a pulsed X-ray source, strong upper limits to its pulsed X-ray flux from the Rossi X-ray Timing Explorer (RXTE) and other satellites have been used to constrain the level of the thermal component from the heated polar caps. In the optical, PSR1706-44 has not been detected. Deep optical observations like those in this work are needed to meaningfully test the outer gap model's prediction of optical emission (Ray et al. 1999).

At present, it is not clear how and where in the pulsar magnetosphere the pulsed non-thermal high energy emission originates. Similarly, the relationship be-

* Based on observations collected at the European Southern Observatory, Paranal, Chile (VLT-UT1 Science Verification Program)

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tween optical pulsed emission and those in the X-ray or gamma-ray bands are unclear. Qualitatively, high energy radiation is believed to occur from incoherent curvature radiation in the outer magnetosphere or by synchrotron emission by energetic electrons near the light cylinder. So far optical pulsations have been detected from the Crab (Cocke et al. 1969) and Vela (Wallace et al. 1977) pulsars, PSR0540-69 (Middleditch & Pennypacker 1985), PSR0656+14 (Shearer et al. 1997) and (possibly) Geminga (Shearer et al. 1998), while ultraviolet pulsations were seen only from the Crab pulsar using the Hubble Space Telescope (Gull et al. 1998). The existing models of optical pulsed radiation (Pacini & Salvati 1987) underpredict the observed fluxes of middle aged pulsars like Geminga and PSR0656+14 by several orders of magnitude. A phenomenological analysis of the optical efficiencies (fraction $\eta_{\rm opt}$ of spin down power radiated in the optical bands) on pulsar parameters show that $\eta_{\rm opt} \propto \dot{P}^2$ for the five observed so far (Goldoni et al. 1995). However, the overall consistency of the models with observed data like phase relationship and the correlation between optical and higher energy bands is not very compelling.

Here we report on the *VLT*-UT1 SV phase observations in the optical of the field including the position of the radio emission from PSR1706-44. The results are discussed in Sect. 2, and their implications in Sect. 3.

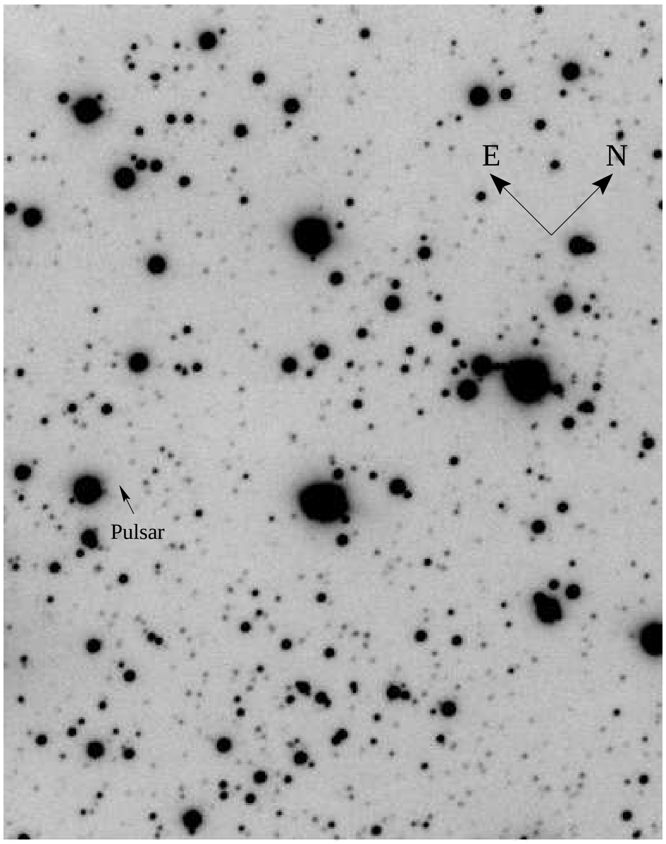

Fig. 1. The field of PSR1706-44 as observed with the Test Camera on *VLT*-UT1. This is the combination of six *V*-images with a total exposure time of 3600s. The field of view shown is $70''$x $88''$. The position of the pulsar is marked with an arrow to the far left of the image. (See Fig. 2 for a more accurate positioning).

2. Observations and Results

The field of PSR1706-44 was observed with the Test Camera on *VLT*-UT1 on August 19, 1998, during SV. (The instrumentation is described in Leibundgut & Renzini 1999.) Six images of 600 seconds each were obtained in the $V-$band. All observations were made with 2x2 binning, a pixel thus corresponds to $\sim 0\farcs09$ on the sky. The raw images were bias subtracted by determining the bias level in the overscan region of the CCD. The two-dimensional bias structure was removed with a master bias frame. Flatfielding was done using a $V-$flat obtained from the science observations on the previous night[1]. The six images were aligned and combined into a final image (see Fig. 1). The quality of this image is very good, with a FWHM of $\sim 0\farcs5$.

Previous attempts to constrain the emission from the pulsar have been severely hampered by a bright nearby star. This star was named Star 1 by Chakrabarty & Kaspi (1998; henceforth CK98), and its magnitude was measured to $V = 17.3$. Due to poorer spatial resolution they could only obtain an upper limit for the pulsar of $R = 18$. The good seeing of the *VLT* image enables us to significantly improve upon this.

In Fig. 2 we show a blow-up of the region around Star 1. Using the radio position of the pulsar (Frail & Goss 1998; Wang et al. 1998), CK98 estimate that the pulsar should lie $2\farcs7$ away from the star. The uncertainty in this position is a combination of errors in the radio position, errors in the astrometric solution to the optical image and a mismatch in aligning radio and optical frames. These are all of the order $0\farcs5 - 0\farcs7$. We have adopted a combined error of $1\farcs0$. This error circle around the position $2\farcs7$ away from Star 1 is shown in Fig. 2.

We carefully searched for the pulsar around that position in the *VLT* image, but no object was found. To estimate an upper limit to the pulsar's emission we constructed a PSF from ten bright stars in the field using the IRAF/DAOPHOT PSF task. We thereafter added a number of artificial stars with different magnitudes to the image. The magnitudes are all measured relative to Star 1 ($V = 17.3$, CK98). The colour terms for the configuration have been measured to be small and are neglected in our study.

To ensure similar backgrounds, the artificial stars were all positioned at a distance of $2\farcs7$ from Star 1. We thus find that stars of magnitude $V = 25.0$ should have been easily seen. Also $V = 25.5$ is clearly visible but an artificial star with $V = 26.0$ is rather faint. If the pulsar is positioned

[1] See http://www.eso.org/paranal/sv/ for details.

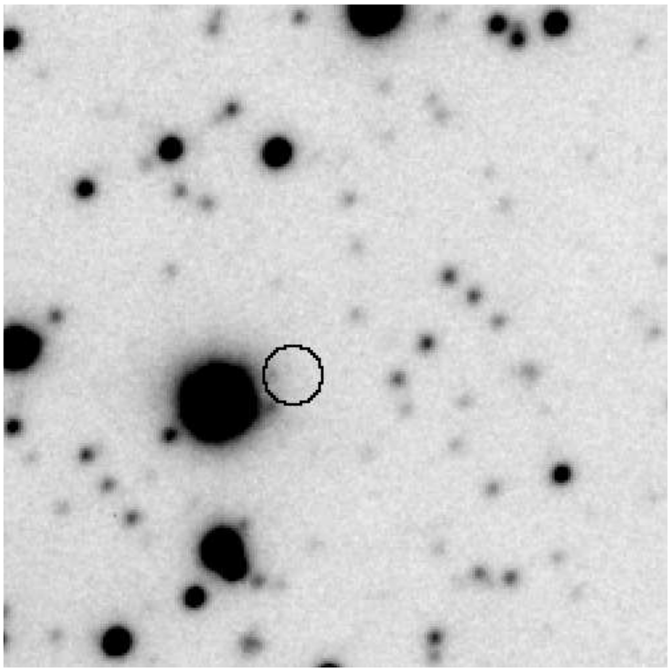

Fig. 2. This is a blow-up of Fig. 1 around Star 1. The expected position of the pulsar is inside the error circle shown. The circle has a radius of 1.″0 and is centered 2.″7 away from Star 1.

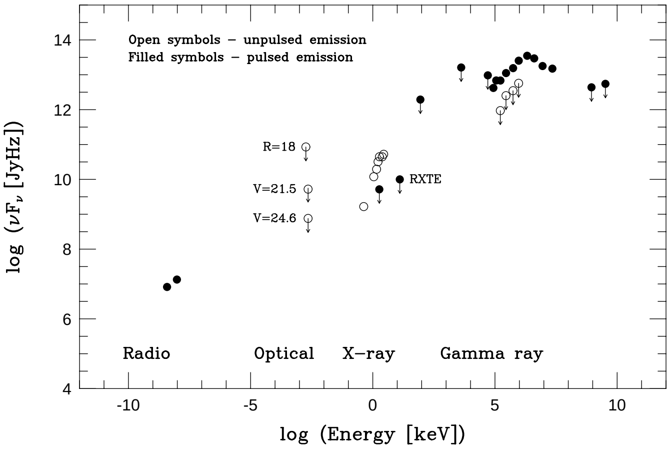

Fig. 3. Multiwavelength spectrum, νF_ν versus ν, for PSR1706-44. Data are taken from the compilations of Thompson et al. (1996, 1999), except for the points marked 'V' which are from this work. The point marked 'RXTE' is from Ray et al. (1999), and that marked 'R' is from CK98. Our two V points correspond to two estimates which should bracket the dereddened upper limit in the visual: $V = 24.6$ assumes minimum extinction ($A_{\rm V} = 0.9$) and the pulsar lying outside the PSF of Star 1, $V = 21.5$ assumses maximum extinction ($A_{\rm V} = 3$) and the pulsar lying close to Star 1 in projection. The point by CK98 is likely to underestimate the extinction.

at the outer end of our error circle, even a $V = 26.0$ star is easily seen. Measuring the background at this distance from Star 1 shows that an artificial star with $V = 25.5$ has in fact a peak pixel value that is more than 3σ above the background. This is thus a firm upper limit for the image.

However, if the pulsar would be positioned much closer to the star than 2.″7, our method of measuring the limiting magnitude becomes more uncertain. In fact, we do see a region of brighter emission in the innermost part of our error circle. This might just be fluctuations in the PSF of the bright star. To estimate how bright a star one could hide in the PSF of Star 1 we instead subtracted artificial stars from this position until a hole appeared in the background. We find that it is possible to hide a rather bright point source ($V = 25.0$) at a distance of $\lesssim 2''$ from the star. As a firm upper limit for a pulsar this close to Star 1 we therefore claim $V = 24.5$.

We conclude that the pulsar is most likely fainter than V=26.0 magnitudes. Deeper exposures are needed to address this question. However, if the pulsar is indeed substantially closer to the bright Star 1, the PSF of that star limits our study. We claim an upper limit of V=24.5 inside our 1.″0 error circle. This is still much fainter than the previous upper limit of CK98. HST resolution would be required to improve upon this estimate.

3. Discussion and Conclusion

The magnitude limits obtained in Sect. 2 have theoretical implications which we briefly mention here. The optical radiation is expected to be produced by tertiary e$^{\pm}$-pairs produced in outer gap discharges. These particle fluxes and energy spectra are in turn dependent upon those of the primary and secondary electrons and the particular radiation mechanism involved, and the optical fluxes may be correlated with the gamma-ray photon fluxes in such models.

Usov (1994, see his Eqn. [24]) has estimated the scaling of the optical vs gamma-ray luminosities expected in the outer gap models by Cheng, Ho & Ruderman (1986a, 1986b) for Vela-like pulsars. Usov's analysis predicts that the frequency integrated optical flux (between 4×10^{14} and 7.5×10^{14} Hz), $F_{\rm opt}$, should scale with the integrated gamma-ray flux as $F_{\rm opt} \gtrsim 4 \times 10^{-4} F_\gamma$. From Fig. 3 we estimate the pulsed F_γ to be 3×10^{13} JyHz for PSR1706-44. For a flat optical spectrum, this gives $F_\nu \gtrsim 3.4 \times 10^{-28}$ erg s^{-1} cm^{-2} Hz^{-1} between 4×10^{14} and 7.5×10^{14} Hz. Assuming F_ν to be the same in both the V and R bands, the magnitudes predicted by the outer gap models by Cheng, Ho & Ruderman (according to Usov 1994) are $R \lesssim 20.0$ and $V \lesssim 19.8$. We will now compare these limits with the observed limits by CK98 and those found in this work.

CK98 found an upper limit to the R magnitude for the pulsar of $R = 18$. It is obvious that the data of CK98 do not constrain the outer gap model, in particular since extinction appears not to have been included by CK98.

We know that extinction in the direction to the pulsar must occur. The photometry of Star 1 by CK98 indicates that $E(B - V) \sim 0.29$. The extinction to the more distant PSR1706-44 is likely to be higher. A rough estimate of the visual extinction is one magnitude per kpc (Spitzer 1978), which would indicate $A_{\rm V} \sim 2$ to the pulsar. This is consistent with the column density, $N_{\rm H} \lesssim 5 \times 10^{21}$ cm^{-2}, indicated by the X-ray data of Finley et al. (1998). This limiting column density translates into $A_{\rm V} \lesssim 3$. A likely range for $A_{\rm V}$ is therefore $0.9 - 3$ magnitudes. The dereddened R magnitude could therefore be much brighter than $R = 18$, and of little value in constraining the outer gap model for PSR1706-44.

The situation is different for our V estimates from the *VLT* observations. Even if we adopt maximum extinction ($A_{\rm V} \sim 3$), and if the pulsar would lie close to Star 1 in projection, the dereddened observed upper limit is only $V \simeq 21.5$, which is ~ 1.7 magnitudes fainter than the limit obtained from Usov's analysis. In Fig. 3 we have included our dereddened upper limit of V (for two combinations of $A_{\rm V}$ and projected distances from Star 1) in a multiwavelength spectrum of the pulsar. Similar spectra are presented by Thompson et al. (1999) for the Crab, Vela and Geminga pulsars, as well as PSR1509-58, PSR1951+32 and PSR1055-52. Our faint limit to the V, in comparison to the predictions of the standard outer-gap model, scaled from gamma-ray flux ($V \lesssim 19.8$), requires a low frequency cutoff in the synchrotron emission spectrum for PSR1706-44.

In the prediction of the ratio of $F_{\rm opt}/F_{\gamma}$ for Vela-like pulsars like PSR1706-44, an important assumption is that the gap averaged magnetic field $\bar{B}$ is approximately equal to the magnetic field at the outer boundary of the outer gap. This average $\bar{B}$ is: $B_{\rm L} \leq \bar{B} \leq (c/\Omega r_{\rm i})^3 B_{\rm L}$, where the subscript 'L' refers to the field at the light cylinder, $r_{\rm i}$ being the inner radius of the outer gap, and $\Omega = 2\pi/P$ is the spin frequency of the pulsar. For small inclination angle χ between the magnetic moment and spin vectors one has $r_{\rm i}\Omega/c = 2/3$, and $\bar{B} \leq (3/2)^3 B_{\rm L}$. This gives the synchrotron cutoff frequency $\nu_{\rm s}$ for tertiary photons near $\sim 10^{14}$ Hz, so that optical emission from a pulsar active in the gamma-ray region should be observable (as estimated above). On the other hand, if $\chi \geq \pi/4$, the synchrotron cutoff frequency is $\sim 10^{13}$ Hz and in this case the flux of optical band radiation may be very small. Our faint limit from the *VLT* for PSR1706-44 in combination with the outer gap model could therefore point to a case of an unaligned rotating neutron star. (This is consistent with an analysis of the photon spectral break in the GeV regime, – see Ray et al. 1999).

As shown in Table 1, PSR1706-44 has similar P and $\dot{P}$ to those of the Vela pulsar. It is therefore of interest that also the Vela pulsar is faint in the optical with $V = 23.65$ and $A_{\rm V} \lesssim 0.4$ (Nasuti et al. 1997). If PSR1706-44 would have the same optical luminosity as Vela, it could have a V magnitude of $V = 26.9$ (if its $A_{\rm V}$ is 0.9 magnitudes, and its distance is 1.8 kpc). Our non-detection of PSR1706-44 in V is consistent with this. However, theory indicates that the optical emission is sensitive to many parameters, so there is certainly room for PSR1706-44 to be intrinsically much brighter than the Vela pulsar. This is also consistent with our results, in particular if PSR1706-44 lies close to Star 1 in projection.

While completing this work, we found out that an independent analysis by Mignani, Caraveo & Bignami (1999), using the same *VLT* SV data as in this work, places a limit on V for PSR1706-44 which is $V \gtrsim 27.5$. In our analysis a star of $V = 27.5$ would have a peak pixel signal less than 1σ above noise level. We doubt such a faint star could be seen, especially if positioned close to Star 1.

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