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Photometry and proper motion of the Vela pulsar*

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Abstract. We present the first UBVR photometry of the Vela Pulsar. All observed colours lie significantly above any Rayleigh-Jeans extrapolation of the ROSAT soft X-ray black body curve. While the U, B and V fluxes can be described by a flat power law, the R point lies about 1 magnitude below the expectation. An evidence for a similar spectral turnover, but at longer wavelength, was also claimed for the Crab Pulsar, another young INS with non-thermal optical emission. However, to account for the Vela R point in term of synchrotron self absorption, the emission geometry of the two pulsars must be different.

In parallel, we have used the new images to re-assess the proper motion of the Vela pulsar, an effect for which vastly different results have been reported in the literature.

Key words: pulsars: Vela pulsar – astrometry

1. Introduction

The optical counterpart of the Vela pulsar was identified by Lasker (1976), on the base of a good positional coincidence of the radio pulsar with a blue field object (his star M). The measured magnitude (m_B = 23.7) was found compatible with the theoretical predictions obtained scaling the optical luminosity of the Crab Pulsar according to the Pacini law (Pacini, 1971). Optical pulsation at the radio period (89 ms) were later observed by Wallace et al. (1977), with a light curve characterized by two sharp peaks well separated in phase. However, the knowledge of the pulsar spectral shape in the optical domain is still rather poor. The object is too faint for optical spectroscopy with the present generation of ground based/space telescopes. Until the first light of the ESO *Very Large Telescope*, multicolor photometry is the only tool available to investigate the spectral shape of the Vela pulsar. In this paper we present the results of multicolor photometry performed at La Silla with the ESO/NTT. In addition to new measures in the U, B and V filters, we present the first observations of Vela in the R band.

Coupled with our archive images, these observations have also been used to obtain a new measure of the pulsar's proper motion. Although an established result, its actual value is still uncertain. The displacements obtained through radio interferometry (Bailes et al 1989, Fomalont et al 1992), and optical differential measurements, using ground based (Bignami & Caraveo 1988, Ögelman et al 1989) and HST images (Markwardt & Ögelman 1994), span a rather wide range from a minimum of 0.038"/y to a maximum of 0.116"/y. For this reason we re-asses the measure of the proper motion comparing, for the first time, relative positions over a period of 20 years.

2. The photometry

We collected several UBVR exposures, ranging between 15 and 30 minutes each, of the Vela Pulsar on 1995 January with EMMI *(ESO Multi Mode Instrument)* at the Nasmyth B focus of the ESO 3.5m NTT, using both the RED/ARM and BLUE/ARM modes (for a description see Melnick, Dekker and D'Odorico 1991). These observations were followed by images of the E5 region (Graham, 1982) to be used for flux calibrations. After the usual cleaning, flat fielding and correction for airmass, the zero point magnitudes were computed averaging data for a number of stars in the calibration field. The computed UBVR magnitudes of the Vela Pulsar are listed in Table 1, where the error values are due mainly to calibration uncertainty. To correct for interstellar extinction we have used the column density values measured in X-rays by Ögelman et al. (1993) ($N_H \sim 10^{20}$ cm^{-2}), and by Page et al. (1996) ($N_H \sim 2.35\ 10^{20}$cm^{-2}). For completeness, the magnitudes dereddened for the extinction reported by Manchester et al. (1978) have also been added. The resulting fluxes are shown in Fig. 1 together with the Rayleigh-Jeans extrapolations of two soft X-ray black body curves inferred from the same ROSAT data. They represent two different sets of assumptions: the lower one has the more standard set of parameters with $T \sim 1.74\ 10^6\ K$ ($N_H \sim 10^{20}$ cm^{-2}) d=500 pc and r=10 km given by Ögelman et al. (1993), the upper one corresponds to the recent analysis of Page et al (1996),

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* Based on observations collected at the European Southern Observatory, La Silla, Chile.

Table 1. Multicolor photometry of the Vela pulsar. Original magnitudes are listed together with the values obtained after correction for different interstellar redenning. We note that our B mag is compatible with the values previously measured by Lasker (1976) B=23.7 ± 0.5, Manchester et al. (1978) B=24.2 ± 0.5 and Ögelman et al. (1989) B=23.7 ± 0.2. Thus, the optical emission of the Vela pulsar appears to be constant within the errors of the measurements. These, in any case, are far bigger than the pulsar secular decrement foreseen on the basis of Pacini's law.

band	*mag*	*band*	$N_H = 10^{20}$ (1)	$N_H = 2.35\ 10^{20}$ (2)	$A_V = 0.4$(3)
U	23.38 ± 0.15	U_0	23.24	23.13	22.68
B	23.89 ± 0.15	B_0	23.80	23.69	23.39
V	23.65 ± 0.10	V_0	23.58	23.49	23.25
R	23.93 ± 0.20	R_0	23.88	23.81	23.63

(1) Ögelman et al. (1993); (2) Page et al. (1996); (3) Manchester et al (1978).

in which the introduction of an atmosphere has the effect of lowering the temperature, $T \sim 9.2\ 10^5$ K, and increasing the N_H, ($N_H \sim 2.35\ 10^{20}$ cm^{-2}), while decreasing the distance (285 ± 120 pc) for the same neutron star radius. In either case our points are seen to fall well above the Rayleigh Jeans extrapolation of the X-ray data. The measured fluxes confirm that the optical emission mechanism is different from the X-ray one, underlying the middle age, intermediate condition of the Vela pulsar, where non-thermal magnetospheric emission coexists with thermal emission from the star surface. Younger objects, $\sim 10^3 y$ old, like the Crab and PSR0540-69, have their electromagnetic emission dominated at all wavelengths by magnetospheric, non-thermal processes. Older objects, $\sim 10^5 y$ old, like Geminga, PSR0656+14 and PSR1055-52 (see e.g. Mignani et al. 1997), exibit thermal emission in optical and X-rays (arising probably from close to the surface) and have non-thermal processes essentially limited to γ-rays, energetically very important. The Vela pulsar phenomenology can be considered a reasonable intermediate step, consistent with the object's age, be it the "canonical" one of 1.1 10^4 yr or the one of $2 - 3\ 10^4$ yr recently obtained by Lyne et al (1996) with the newly measured breaking index. It would also be interesting to investigate the optical behaviour of PSR1706-44, of similar age, detected in soft X-rays (Becker et al., 1995), and also detected in γ-rays (Thompson et al. 1996), although its greater distance will make it a challenging target for optical observations.

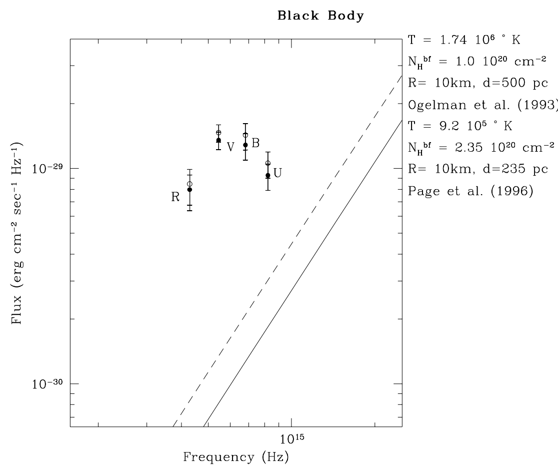

Fig. 1. The UBVR fluxes of PSR 0833-45 compared with the RJ extrapolation of the ROSAT soft X ray spectral fits obtained by Ögelman et al (1993) - solid line - and by Page et al. (1996) - dashed line- using the same data but a different model spectrum. For consistency, the colours have been dereddened for different N_H values. Ögelman et al. (1993) - filled circles - and Page et al. (1996) - open circles.

Our four colours are not accountable in terms of simple spectral shapes. While black body curves are clearly not adequate to describe the data, nor is there any reason to believe that they should, the low R point prevents all data to be fitted with a single power law.

This happens to be the case also for the colours of the Crab pulsar, but certainly not for PSR 0540-69, the UBVR fluxes of which have been plotted in Fig. 2 as recomputed from the fluxes of Percival et al. (1993) and the magnitudes published by Middleditch et al (1987). We note a possible discrepancy between our graph and Fig. 1 of Middleditch et al. (1987), where they see the evidence for an excess of ultraviolet flux for Crab and PSR0540-69. Using the same magnitude values, we find no evidence of such an ultraviolet excess for these two objects nor we see any excess in our data for the Vela Pulsar. In the case of the Crab, our U flux is consistent with the more recent data of Percival et al. (1993), who also found no ultraviolet excess. This discrepancy could be explained by the approach used in the magnitudes to monochromatic fluxes conversion by Middleditch et al. (1987)

The UBV colors of the Vela pulsar appear to follow a rather flat spectral distribution. However, the R flux decrement represents a clear spectral turnover in the red region of the spectrum. Of course, further observations at longer wavelength are needed to confirm this trend.

In fact, the only young pulsar studied at longer wavelengths is the Crab one, for which a spectral turnover in the NIR was observed (e.g. Penny 1982; Middleditch et al 1983; Ransom et al, 1994). It has been proposed that this may be due to synchrotron self-absorption (Penny 1982; Middleditch et al 1983). In this case, one would expect the turnover frequency ν_t to be dependent on the radius R and on the pulsar's magnetic field $B(R)$ at the emitting region, according to the relation $\nu_t \sim B(R)^{2/3} R^{1/3}$. Assuming the emission to take place close to the pulsar's light cylinder $R_{lc} = cP/2\pi$, or in a region located at a constant fraction of it, we expect the turnover frequency to scale as $B(R_{lc})^{2/3} P^{1/3}$.

Table 2. Vela pulsar proper motion prior to our work.

	Optical data			Radio data	
	Bignami & Caraveo 1988	*Ögelman et al. 1989*	*Markwardt & Ögelman 1994*	*Bailes et al.* 1989*	*Fomalont et al. 1992*
μ	< 60 mas	38 mas $\pm$ 8 mas	49 mas $\pm$ 4 mas	59 mas $\pm$ 5 mas	116 mas $\pm$ 62 mas
μ_α		-26 mas $\pm$ 6 mas	-41 mas $\pm$ 3 mas	-48 mas $\pm$ 4 mas	-67 mas $\pm$20 mas
μ_δ		28 mas $\pm$ 6 mas	26 mas $\pm$ 3 mas	34 mas $\pm$ 2 mas	-95 mas $\pm$ 75 mas

After correction for the motion of the Sun and for the rotation of the Galaxy they obtain $\mu_\alpha = -40$ mas $\pm$ 4 mas and μ_δ = 28 mas $\pm$ 2 mas

Table 3. Observations of the Vela Pulsar used to compute the proper motion. The relative displacements are computed relative to the 1975 frame, the quoted uncertainties include stars' centering errors as well as errors in the rebinning/rotation procedures.

Epoch	*Telescope*	*Pixel size*	*Exp. Time*	$\Delta\alpha$	$\Delta\delta$
1975.2	CTIO 4m	-	45 min	$0'' \pm 0''.05$	$0'' \pm 0''.05$
1987.1	ESO 3.6m	$0''.67$	30 min	$-0''.46 \pm 0''.06$	$0''.21 \pm 0''.06$
1988.1	ESO 3.6m	$0''.67$	30 min	$-0''.52 \pm 0''.09$	$0''.31 \pm 0''.05$
1990.1	ESO NTT	$0''.26$	85 min	$-0''.73 \pm 0''.05$	$0''.40 \pm 0''.05$
1995.1	ESO NTT	$0''.36$	30 min	$-0''.92 \pm 0''.02$	$0''.45 \pm 0''.02$

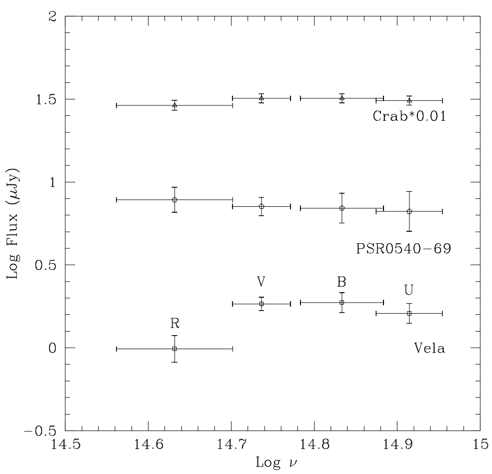

Fig. 2. The $UBVR$ fluxes of PSR0833-45 computed from the magnitudes listed in Table 1. These fluxes are compared to those of PSR0531+21 and PSR0540-69 which have been recomputed from the values in literature (Percival et al., 1993; Middleditch et al., 1987). The fluxes of Crab have been normalized for a better comparison.

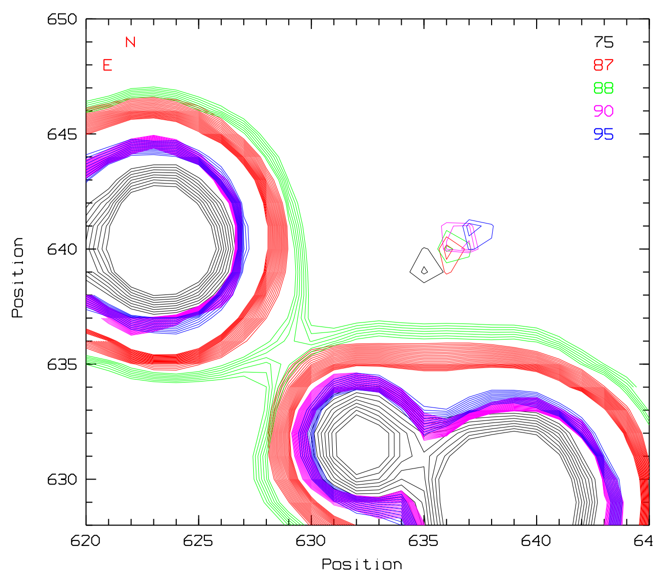

Fig. 3. Contour plots of the five data sets used, showing the overall motion of the Vela Pulsar over a time span of $20yr$. X and Y axes are in pixels and are aligned with RA and DEC, respectively. The overall displacement between the first and the last observation is $\sim 1''$, with the 1987, 1988 and 1990 data sets showing the pulsar at intermediate positions.

This would shift the spectral turnover of Vela redwards with respect to that of the Crab, contrary to what seems to be the case. On the other hand, an emitting region located at a fraction of the light cylinder 5 times smaller than that of the Crab could reconcile our R point with the synchrotron self absorption scenario. The plausibility of such a requirement is hard to gauge in view of the paucity of the data available and of the oversimplification of our assumptions. In fact, the dramatic difference in the multifrequency behaviour of the Crab and Vela pulsars (see e.g. Thompson et al.,1994), as well as the differences in duty cycle and shape of their optical light-curves, argue in favour of a marked difference in the geometry of their emitting regions. A detailed modelling of the emission geometry of the gamma-ray pulsar magnetospheres has been developed by Romani and Yadigaroglu (1995) in the context of the outer gap model. They note that while the optical emission of the Crab pulsar must be produced over much of the outer gap, the Vela pulsar light curve seems "consistent with an origin near the null charge surface", pointing towards an inner emitting region for the Vela pulsar. New NIR colours could therefore also yield better ideas on the emission geometry.

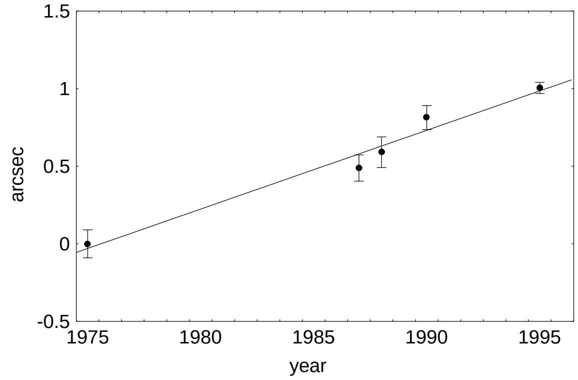

Fig. 4. Linear fit to the positions of the Vela Pulsar.

3. The proper motion

The proper motion of the Vela pulsar has been addressed a number of times using both radio and optical data (see Table 2 for a summary of the values obtained so far). After the upper limit of 60mas yr^{-1} set by Bignami & Caraveo (1988), the proper motion has been measured by Ögelman et al. (1989) and Markwardt & Ögelman (1994) using optical data, and by Bailes et al. (1989) and Fomalont et al. (1992) using radio data. The measured values are seen to leave open a significant uncertainty. To revisit the problem and to better assess the value of the proper motion we have used our new images of the Vela pulsar field together with images in our archive. We have observed Vela four times: in January 1987, 1988, 1990 and 1995. The first and second observations were performed with the ESO 3.6m, while the 1990 and 1995 ones with the ESO NTT (see Table 3 for a summary). In order to obtain an accurate measure of the pulsar position and to avoid any centroid shift due to atmospheric differential refractions, we used only observations performed at small zenith angles and through the same filter, i.e., the Johnson B one.

In order to extend as much as possible the time interval covered by our analysis, we have digitized the "broad-band blue" IIIa-J plate of the Vela field, published by Lasker (1976) in its discovery paper and kindly provided to us by the author. Five images, covering 20 yrs, can thus be used. Since the data have been taken with different telescopes and detectors, first we had to rebin and tilt the images to match exactly the same scale and orientation. As a reference, we used the NTT 1995 frame, up to now the best image of the field, owing to the best seeing conditions ($\sim$ 0.8"). The aligment of the different frames was then performed with MIDAS, after computing the coordinate transformations from a linear fit to the position of a set of common reference stars. The final result was very good, with all the reference stars overlapping within a few hundreths of the NTT/EMMI pixel size (0.36").

In order to have a first guess of the Vela Pulsar displacement relative to the field stars, we have superimposed the contour plots of the five observations. This is shown in Fig. 3. While the positions of reference stars do not show any significant variation, the motion of the pulsar to the northwest is evident, with an overall displacement of about one arcsec from 1975 to 1995. The proper motion of the Vela pulsar was thus obtained fitting the angular displacements (listed in Table 3) relative to the 1975 position. A least-squares fit to the data was performed and is shown in Fig. 4 . The resulting proper motion of the pulsar is:

$$\mu_\alpha = -47 \text{ mas} \pm 3 \text{ mas yr}^{-1} \; \mu_\delta = 22 \text{ mas} \pm 3 \text{ mas yr}^{-1}$$

The total proper motion is 52 ± 5 mas yr^{-1} with a best fitting position angle of $\sim$ 295°. The proper motion of the pulsar appears completely unrelated to the jet seen in soft X ray to protrude south from the pulsar (Markwardt & Ögelman, 1995). For the assumed "canonical" distance to the Vela Pulsar of $\sim$ 500 pc, the measured proper motion results in a transverse velocity of 128 ± 17 km s^{-1} which is on the lower side of the average for the radio pulsar sample.

4. Conclusions

The first observation of Vela pulsar in R, presented jointly with photometry in U, B and V, provides the most complete picture so far of the source optical emission. As expected, the observed fluxes cannot be explained by thermal emission from the neutron star surface, i.e. by the same process which powers the pulsar in soft X-rays. The non thermal nature of the Vela optical emission, also inferred from its light curve shape, is independently confirmed. As to its colours, certainly no U "bump" is present in them, as suggested for the Crab pulsar and PSR 0540-69 by Middleditch et al. (1987). In fact, a reanalysis of their data shows that effect to be probably spurious. No single power law can fit all the Vela points, the R colour being at least 1 mag fainter than expected on the basis of UBV colors. The possible spectral turnover thus suggested could be due to synchrotron self absorption, a process already invoked for the Crab pulsar. Hovever, detailed modelling of the geometry of the emitting regions is needed to understand the nature of such a turnover. Obviously, more colours in the NIR region would be equally important to clarify the source spectral shape.

At the same time, a new measure of the Vela pulsar proper motion has been obtained. We find that the pulsar is moving at 52 ± 5 mas yr^{-1} at a position angle of 295°. Since our proper motion study covers a period of 20 years, the present result can be considered reliable. In particular, our value is compatible with the previous measurements of Markwardt and Ögelman (1994) and Bailes et al. (1989), while is clearly incompatible with the ones of Ögelman et al. (1989) and Fomalont et al (1992). Thus, our measurements make a final case for the Vela pulsar proper motion to be around 50 mas/y. A better assessment will only be possible through accurate HST astrometry, currently in progress, which could also yield a measurable annual parallax, ending the current debate on the Vela pulsar/SNR distance.

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