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On the velocity of the Vela pulsar

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Abstract. It is shown that if the shell of the Vela supernova remnant is responsible for nearly all the scattering of the Vela pulsar, then the scintillation and proper motion velocities of the pulsar can only be reconciled with each other in the case of nonzero transverse velocity of the scattering material. A possible origin of large-scale transverse motions in the shell of the Vela supernova remnant is discussed.

Key words. pulsars: individual: Vela – ISM: individual objects: Vela supernova remnant – scattering

1. Introduction

The Vela pulsar is one of the best studied radio pulsars and was the first one found to be associated with the supernova remnant (SNR) (Large et al. 1968). In spite of its relative proximity to the Earth, there is still no consensus on the value of its (transverse) velocity, which is connected with the yet unsolved problem of the distance to the Vela pulsar/Vela SNR. The first attempt to estimate the pulsar velocity was made by Bignami & Caraveo (1988), whose optical measurments gave an upper limit on the pulsar proper motion ($<60\,\mathrm{mas\,yr^{-1}}$). However, even the maximum admissible value of the pulsar proper motion was found to be too low to explain the pulsar offset from the apparent geometrical centre of the Vela SNR, which questions the pulsar/SNR association. Later, it was recognized (e.g. Seward 1990; Aschenbach et al. 1995) that the real extent of the Vela SNR is much larger than was accepted in early studies, so now there can be no doubt that the Vela pulsar and the Vela SNR are the remnants of the same supernova explosion. However, this association has caused some problems in estimating the pulsar velocity.

Wallerstein & Silk (1971) questioned for the first time the "canonical" value of the distance to the Vela SNR of 500 pc given by Milne (1968; see also Taylor et al. 1993) and suggested that this distance should be reduced to some smaller value ($\simeq$ 250 pc). Since that time many additional arguments in support of this suggestion have been put forward (Ögelman et al. 1989; Oberlack et al. 1994; Jenkins & Wallerstein 1995; Aschenbach et al. 1995; Bocchino et al. 1999; Cha et al. 1999; Cha & Sembach 2000)[1]. One of the arguments (proposed by Ögelman et al. 1989 and repeated by Oberlack et al. 1994; Cha et al. 1999) was based on the comparison of the Vela pulsar transverse velocity (inferred from the new estimate of the pulsar proper motion by Ögelman et al. 1989) with the scintillation velocity (reported by Cordes 1986). It is known that proper motion velocities of pulsars show significant correlation with pulsar velocities inferred from interstellar scintillation measurements (e.g. Lyne & Smith 1982; Gupta 1995). Therefore, assuming that the scintillation velocity $V_{\rm iss}$ is a "true" value of the pulsar transverse velocity, Ögelman et al. (1989) suggested that $V_{\rm iss} = 53 \pm 5\,\mathrm{km\,s^{-1}}$ (Cordes 1986) could be reconciled with the proper motion $\mu \simeq 38 \pm 8\,\mathrm{mas\,yr^{-1}}$ if the distance to the Vela pulsar (and the Vela SNR) is about 290 ± 80 pc. The distance reduction might be even more dramatic if one takes the recent high-precision estimate of the Vela pulsar proper motion ($52 \pm 3\,\mathrm{mas\,yr^{-1}}$) obtained by De Luca et al. (2000; see also Nasuti et al. 1997). The situation with the distance to the Vela SNR was "improved" after Gupta et al. (1994) showed that the scintillation velocity calculation formula used by Cordes (1986) underestimates $V_{\rm iss}$ by factor of 3. The revised value of the scintillation velocity of the Vela pulsar of $152\,\mathrm{km\,s^{-1}}$ better corresponds to the proper motion velocity of $123\,\mathrm{km\,s^{-1}}$ (for the distance to the pulsar of 500 pc

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[1] We critically analysed these arguments (Gvaramadze 2000a,b) and came to the conclusion that there are no weighty reasons to revise the "canonical" distance of 500 pc.

and $\mu = 52\,\mathrm{mas\,yr^{-1}}$). However, the real situation is a bit more complicated.

It should be noted that the calculations of Gupta (1995) were based on the assumptions that the scattering material is concentrated in a thin screen and that the screen is placed midway between the observer and the pulsar. Although the first assumption is realistic, the second one is not suitable in the case of the Vela pulsar. Indeed, it is believed that the scattering irregularities responsible for the enhanced scattering of the Vela pulsar (Backer 1974) are localized in a thin screen rather than uniformly distributed along our line of sight to the pulsar (Backer 1974; Lee & Jokipii 1976, see also Williamson 1974), and that the scattering screen resides close to the pulsar and could be associated with the shell of the Vela SNR (Desai et al. 1992; Taylor & Cordes 1993; Gwinn et al. 1993, see however Gwinn et al. 1997, 2000 and cf. Cordes & Rickett 1998). The asymmetrical location of the screen implies (see Sect. 2) that the actual value of the scintillation velocity should be considerably larger than that given by Gupta (1995) and that the scintillation velocity is not equal to the proper motion velocity.

In this paper, we show that if the scattering of the Vela pulsar indeed occurs in the shell of the Vela SNR then the scintillation velocity could be reconciled with the pulsar proper motion velocity only if the scatterer has a nonzero transverse velocity. A possible origin of large-scale transverse motions in the Vela SNR's shell is discussed.

2. Scintillation and proper motion velocities

The scintillation velocity for an asymmetrically placed thin scattering screen is (Gupta et al. 1994; Gupta 1995):

$$V_{\mathrm{iss}} = 3.85\ 10^4\,\frac{(\nu_{\mathrm{d,MHz}} D_{\mathrm{kpc}} x)^{1/2}}{f_{\mathrm{GHz}} t_{\mathrm{d}}}\,\mathrm{km\,s^{-1}}\,, \tag{1}$$

where $\nu_{\mathrm{d,MHz}}$ and t_{d} are the scintillation bandwidth and the time-scale measured respectively in MHz and seconds, D_{kpc} is the distance from observer to pulsar in kpc, $x = D_{\mathrm{o}}/D_{\mathrm{p}}$, D_{o} and D_{p} are the distances from observer to screen and from screen to pulsar, f_{GHz} is the frequency of observation in units of GHz. For $\nu_{\mathrm{d,MHz}} = 0.001$, $t_{\mathrm{d}} = 5.6$, $f_{\mathrm{GHz}} = 1$ (Cordes 1986), $D_{\mathrm{kpc}} = 0.5$, and assuming that $x = 1$, one finds for the Vela pulsar that $V_{\mathrm{iss}} = 152\,\mathrm{km\,s^{-1}}$ (Gupta 1995). As we mentioned in Sect. 1, Desai et al. (1992) showed that the scattering screen is close to the pulsar. Assuming that $D = 500$ pc, they found that $D_{\mathrm{o}}/D \simeq 0.81$, and that this value could be increased up to 0.96 if 5% of the scattering of the Vela pulsar is due to the effect of the Gum Nebula. The latter value of D_{o}/D is expected if the scattering material is mainly concentrated in the shell of the Vela SNR of angular diameter of 5° (the figure accepted in early studies of the Vela SNR). Assuming that the Vela SNR's shell is indeed the main scatterer of the Vela pulsar and using the currently adopted angular size of the Vela SNR of $\simeq$7°, one has $D_{\mathrm{o}}/D \simeq 0.94$ or $x = 15.7$, and correspondingly $V_{\mathrm{iss}} \simeq 600\,\mathrm{km\,s^{-1}}$. In the observer's reference frame, the scintillation velocity is connected with the pulsar proper motion velocity

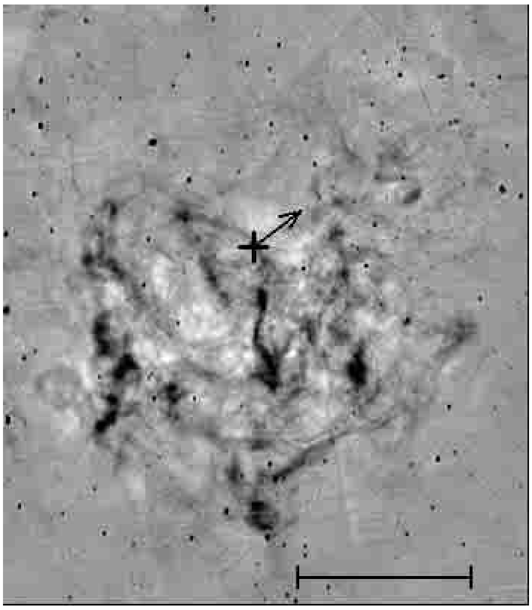

Fig. 1. The 843 MHz image of the central part of the Vela SNR (adopted from Bock et al. 1998). Position of the Vela pulsar is indicated by a cross. The arrow shows the direction of the pulsar proper motion velocity (Bailes et al. 1989). North is up, east at left. The horizontal bar is 1° long

$$V_{\mathrm{pm}} = 4.74 \mu D_{\mathrm{kpc}}\,\mathrm{km\,s^{-1}}\,, \tag{2}$$

where μ is measured in $\mathrm{mas\,yr^{-1}}$, by the following relationship (cf. Gupta et al. 1994; Cordes & Rickett 1998):

$$V_{\mathrm{iss}} = \Big[x^2 V_{\mathrm{pm}}^2 - 2x(1+x)V_{\mathrm{pm}}V_{\mathrm{scr},\parallel} + (1+x)^2 V_{\mathrm{scr},\parallel}^2 + (1+x)^2 V_{\mathrm{scr},\perp}^2\Big]^{1/2}\,, \tag{3}$$

where $V_{\mathrm{scr},\parallel}$ and $V_{\mathrm{scr},\perp}$ are the components of the transverse velocity of the screen, correspondingly, parallel and perpendicular to the vector of the pulsar proper motion velocity. In (3) we neglected small contributions from the differential Galactic rotation and the Earth's orbital motion around the Sun. If $V_{\mathrm{scr}} = 0$, one has $V_{\mathrm{pm}} = V_{\mathrm{iss}}/x \simeq 38\,\mathrm{km\,s^{-1}}(D_{\mathrm{kpc}} = 0.5)$, i.e. about 3 times smaller than that from Eq. (2). These velocity estimates could be reconciled only if the distance to the Vela pulsar is $D_{\mathrm{kpc}} = 0.05(x/15.7)^{-1}$, which is too small to be likely. The pulsar, however, could be placed at its "canonical" distance if $V_{\mathrm{scr}} \neq 0$.

Figure 1 shows the 843 MHz image (Bock et al. 1998) of the central part of the Vela SNR, known as the radio source Vela X (Milne 1968). A considerable fraction of the radio emission from Vela X originates in filamentary structures, one of which crosses the Vela pulsar position. This filament (or rather its part to the south of the pulsar) is known as a radio counterpart of the Vela X-ray "jet" discovered by Markwardt & Ögelman (1995). In Gvaramadze (1998, 1999), we found that some of radio filaments of the Vela X and the X-ray "jet" show a fairly good correlation with optical filaments, and concluded that the "jet" is a dense filament in the Vela SNR's shell, which is projected by chance near the line of sight to the Vela pulsar. We also suggested that filamentary structures visible throughout the Vela SNR in radio, optical and X-ray ranges have a common nature[2] and that their origin is connected with projection effects in the Rayleigh-Taylor unstable shell of the remnant. The Rayleigh-Taylor instability results from the impact of the supernova ejecta/shock with the pre-existing wind-driven shell created by the supernova progenitor star (see Gvaramadze 1999), and induces in the shell large-scale transverse motions (laterally expanding domelike deformations of the shell). The existence of laterally expanding deformations naturally explains (Gvaramadze 1999) the "unusual" velocity field inferred by Jenkins et al. (1984) from the study of absorption lines in spectra of background stars (see also Jenkins et al. 1976; Danks & Sembach 1995). The high-velocity absorption features were found not only in the central part of the Vela SNR but also near the edges of the remnant, which suggests that the expansion velocity of the shell deformations has comparable radial and transverse components. The same conclusion follows from the interpretation of UV spectra of face-on and edge-on shock waves in the Vela SNR (Raymond et al. 1997). A characteristic expansion velocity of shell deformations inferred from the absorption data and UV spectra is about $100\,\mathrm{km\,s^{-1}}$, while some portions of the shell expand with much higher velocities.

Proceeding from the above, we suggest that the radio filament projected on the Vela pulsar is a large-scale deformation of the Vela SNR's shell viewed edge-on, and that this deformation has a significant transverse velocity. We assume that the deformation lies on the approaching side of the Vela SNR's shell and suggest that the turbulent material associated with the shell deformation is responsible for the scattering of the Vela pulsar (cf. Desai et al. 1992). The line of sight extent of the scattering material could be estimated to be $\simeq$1.2–1.7 pc (for $D = 500$ pc) given that the width of the filament is $\simeq 2'$–$3'$ (Milne 1995; Bock et al. 1998) and assuming that the characteristic size of the shell deformation is $\simeq 40'$–$50'$. The geometry (the curvature) of the filament projected on the Vela pulsar suggests that this part of the shell expands in the northwest direction, i.e. just parallel to the vector of the pulsar proper motion velocity (Ögelman et al. 1989; Bailes et al. 1989). For $V_{\mathrm{scr},\perp} = 0$, one has from (3) that

$$V_{\mathrm{scr}} = V_{\mathrm{scr},\parallel} \simeq \frac{xV_{\mathrm{pm}} \pm V_{\mathrm{iss}}}{x+1} \,. \qquad (4)$$

For the transverse velocity of the pulsar of $\simeq 120\,\mathrm{km\,s^{-1}}$ (i.e. for $D = 500$ pc) and for $x = 15.7$ and $V_{\mathrm{iss}} \simeq 600\,\mathrm{km\,s^{-1}}$, one has that V_{scr} is 80 or $150\,\mathrm{km\,s^{-1}}$. The first estimate is quite reasonable, while the second, though not impossible, looks less likely. It should be noted, however, that Eq. (4) gives reasonable values for V_{scr} not only for $D = 500$ pc. E.g. for $D = 250$ pc, one finds that V_{scr} is equal to 30 or $80\,\mathrm{km\,s^{-1}}$. From this, we conclude that the scintillation data taken alone do not allow us to put meaningful limits on the distance to the Vela pulsar and therefore to get a reliable estimate of the transverse velocity of the pulsar. The forthcoming direct measurement of the distance to the Vela pulsar through its parallactic displacement (see De Luca et al. 2000) will solve the problem.

3. Discussion

The main assumption made in this paper is that the enhanced scattering of the Vela pulsar is due to the effect of the Vela SNR. This assumption is based on the result of Desai et al. (1992) that the scattering material could be associated with the shell of the Vela SNR (see Sect. 2). In this case, the parameter x has a fixed value, which depends only on the angular size of the Vela SNR's shell, and therefore is independent of the distance to the pulsar.

It should be noted, however, that the result of Desai et al. (1992) was derived from use of scintillation observables (see Blanford & Narayan 1985; Gwinn et al. 1993). The referee (J. Cordes) pointed out that the quite large uncertainties in observables result in uncertainty in the value of the parameter x. He attracted our attention to the papers by Gwinn et al. (1997, 2000), from which follows that the value of x could be much smaller than that adopted in our paper. The values of x given in these papers (respectively, $x = 2.7(D/0.5\,\mathrm{kpc})^{-1}$ and $x = 1.5(D/0.5\,\mathrm{kpc})^{-1}$) imply that the scattering material cannot be connected with the Vela SNR. We now discuss this possibility.

For $x = 2.7(D/0.5\,\mathrm{kpc})^{-1}$ (Gwinn et al. 1997), one obtains[3] $V_{\mathrm{iss}} = 250\,\mathrm{km\,s^{-1}}$. Note that now V_{iss} is independent of D since $x \propto D^{-1}$ (see e.g. Gwinn et al. 1993 and Eq. (1)). One can see that V_{iss} could be reconciled with V_{pm} only if $V_{\mathrm{scr}} \neq 0$: $V_{\mathrm{scr}} = 157$ or $-22\,\mathrm{km\,s^{-1}}$ for $D = 0.5$ kpc; $V_{\mathrm{scr}} = 91$ or $-13\,\mathrm{km\,s^{-1}}$ for $D = 0.25$ kpc. These transverse velocities are too high to be attributed to the expansion of the shell of the Gum Nebula[4] (cf. Reynolds 1976 with Wallerstein et al. 1980), though it is not impossible that they could characterize the expansion of a foreground small-scale H II region projected by chance on the Vela pulsar.

For $x = 1.5(D/0.5\,\mathrm{kpc})^{-1}$ (Gwinn et al. 2000), one obtains $V_{\mathrm{iss}} = 186\,\mathrm{km\,s^{-1}}$. One can show that just for this value of x (or more exactly for $x = (152/123)^2 = 1.53$) the

[2] This suggestion implies that the radio source Vela X is a part of the Vela SNR's shell (see also Milne & Manchester 1986; Milne 1995; but see e.g. Frail et al. 1997; Bock et al. 1998; Chevalier 1998 for a different point of view).

[3] For the sake of simplicity, we use here the same values of $\nu_{\mathrm{d}}, t_{\mathrm{d}}$ and f as in Sect. 2.

[4] The enhanced scattering of the Vela pulsar was originally ascribed to the Gum Nebula (Backer 1974; see also Cordes et al. 1985).

transverse velocity of the screen could be equal to zero (see Eq. (4)), and therefore $V_{\rm pm} = V_{\rm iss}/x$.

Although these estimates show that the situation with the scattering screen is indeed quite uncertain, we believe that the enhanced scattering of the Vela pulsar is most likely connected with the shell of the Vela SNR. An argument in support of this belief is the fact that the elongated scattering disk of the Vela pulsar (Gwinn et al. 1997) is nearly perpendicular to the magnetic field of the radio filament projected on the Vela pulsar.

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