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Low-Frequency Observations of the Vela Supernova Remnant and their Implications

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Abstract. We have studied the Vela supernova remnant in the light of the 34.5 MHz observations made with the GEETEE low frequency array. The flux densities of Vela X and YZ at 34.5 MHz are estimated to be 1800 and 3900 Jy respectively. These values, along with those from earlier observations at higher frequencies, imply spectral indices ($S \propto \nu^{\alpha}$) of -0.16 ± 0.02 for Vela X and -0.53 ± 0.03 for Vela YZ. This situation is further substantiated by the spectral-index distribution over the region obtained between 34.5 and 408 MHz.

The spectral-index estimates, along with other known characteristics, strengthen the earlier hypothesis that Vela X is a plerion, while Vela YZ is a typical shell-type supernova remnant. We discuss the implications of this result.

Key words: Vela supernova remnant—Vela pulsar—SNR-PSR association

1. Introduction

Vela XYZ is a large ($\approx 7^{\circ}$) non-thermal radio source in the Vela-Puppis complex at a distance of ≈ 500 pc. It has been commonly believed that the source is the remnant of the supernova explosion which also left behind the pulsar PSR 0833 − 45 (referred to as the Vela pulsar). Such an association would imply an age for the remnant of $\approx$ 10,000 yr corresponding to the spin-down age of the pulsar.

Vela XYZ has been well studied over a wide range of wavelengths, from the radio to X-rays. In the radio, Rishbeth (1958) mapped the Vela region at 19.7 and 85 MHz. Later, maps of this region were made at several frequencies up to 5 GHz (Harris 1962; Mathewson, Healey & Rome 1962; Milne 1968; Davies & Gardner 1970; Day, Caswell & Cooke 1972; Milne 1980). Fig. 1 shows a 2.7-GHz map of the region with a resolution of 8′.2 (Day, Caswell & Cooke 1972). Vela XYZ is the extended object lying within $08^{h}25^{m} \leqslant \alpha \leqslant 08^{h}56^{m}$ and $-48^{\circ} \leqslant \delta \leqslant -41^{\circ}$. Three bright concentrations, Vela X (0833 − 46), Vela Y (0844 − 44) and Vela Z (0848 − 46), stand out in the figure. Optical images of the remnant (Elliott, Goudis & Meaburn 1976) show that a majority of the observed Hα filaments follow the radio contours in high-frequency maps. The ultraviolet maps of Miller (1973) show a similar situation. Einstein Observatory

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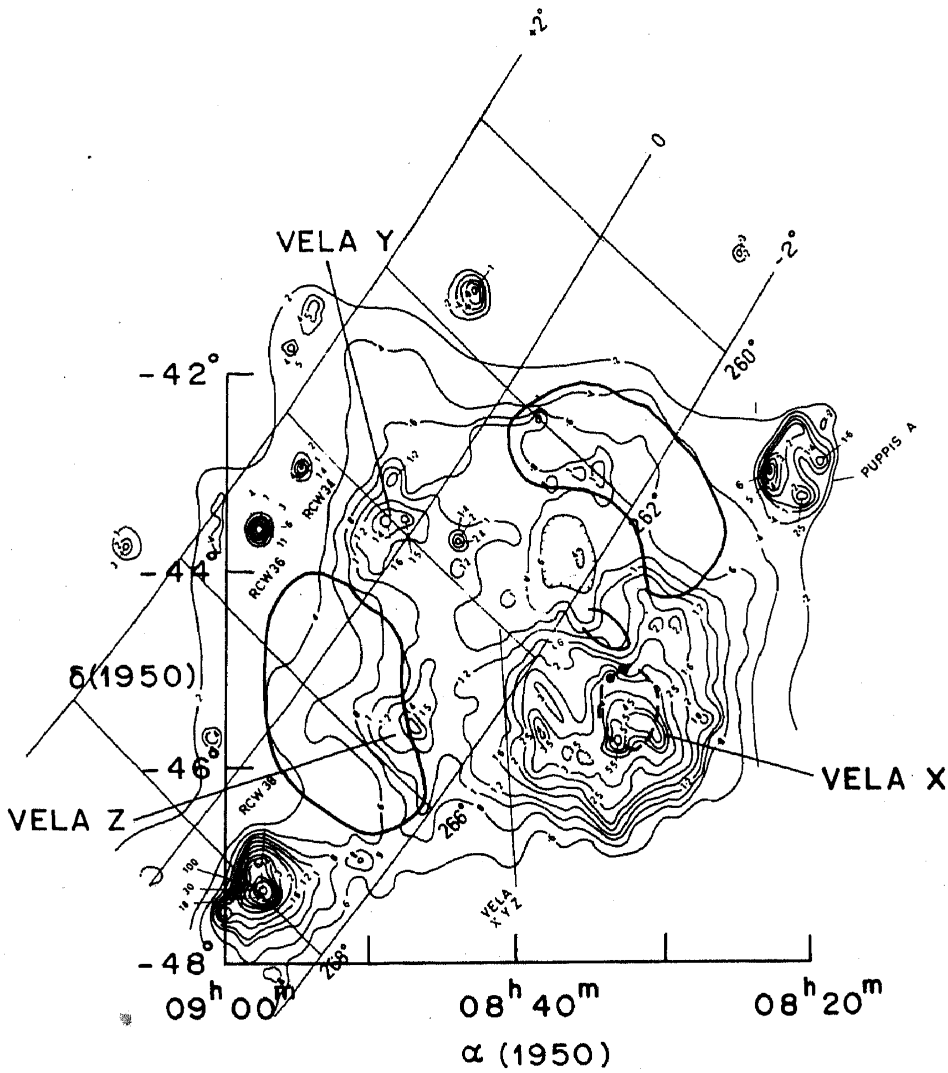


Figure 1. A 2.7 GHz map of the Vela-Puppis region with a resolution of 8.′2 (Day, Caswell & Cooke 1972). The contours are labelled in units of K. The thick solid lines indicate boundaries of significant X-ray emission in the 0.2–1.0 keV energy range (Kahn *et al.* 1985). The broken lines mark the boundary of the region from where the X-ray emission in the energy range of 1.4–3.5 keV has been observed (Harnden *et al.* 1985). The filled circle indicates the position of the pulsar PSR 0833−45, while the arrow indicates its present direction of motion as observed by Bailes *et al.* (1989).

measurements of the Vela supernova remnant (SNR) by Kahn *et al.* (1985) and Harnden *et al.* (1985) reveal a 1° nebula of *hard* emission (shown by broken lines in Fig. 1) and a more extensive 5° emission region covering the rest of the remnant (solid lines in Fig. 1). It may be seen in Fig. 1 that the harder emission, which is believed to be non-thermal, stretches from the pulsar PSR 0833−45 (shown as a filled circle) towards the peak of emission in Vela X. The extended X-ray emission is believed to be thermal in origin and roughly follows the boundary of the radio remnant, although there is no X-ray emission in the region of Vela Y.

2. The controversy

Based on its radio morphology, spectral index, polarization at high radio frequencies, the presence of non-thermal X-rays and the apparent association of the pulsar PSR 0833 − 45 with the remnant, Weiler & Panagia (1980) suggested that Vela X is a plerion (*i.e.* a pulsar-energized nebula), while Vela Y and Z have the characteristics of a typical shell remnant. They also suggested that Vela X is directly powered by PSR 0833 − 45, much as the Crab Nebula is powered by PSR 0532 + 21. Subsequently, Milne & Manchester (1986) raised several objections to this scenario:

1. PSR 0833 − 45 is about 40′ from the radio peak of Vela X. The possibility that the pulsar has moved away from an earlier position at the centre of Vela X seemed to be inconsistent with the available limits on the proper motion of the pulsar.
2. The non-thermal X-ray nebula extending towards the radio peak of Vela X is very weak in comparison to that of the Crab Nebula. Milne & Manchester (1986) suggest that the corresponding radio nebula should be much weaker than Vela X.
3. They suggested that the spectral index of Vela X is not significantly different from that of Vela Y and Z.

However, based on the peak brightness temperatures of Vela X, Y and Z at different frequencies, Weiler & Sramek (1988) have reaffirmed that the spectrum of Vela X is flatter than the rest of the remnant thus consistent with its origin as a pulsar-driven remnant. They conclude their discussion of Vela XYZ by saying new measurements at low frequencies and more accurate spectral index distribution determinations are obviously desirable.

In this paper, we report observations of the Vela SNR at 34.5 MHz and discuss the implications of our improved spectral-index estimates.

3. The present observations

Recently, a wide-field survey at 34.5 MHz has been completed (Dwarakanath & Udaya Shankar 1990) using the GEETEE*–the low-frequency telescope at Gauribidanur (latitude 13°36′12″). The observations were made in the transit mode, performing one-dimensional synthesis along the meridian to map the entire observable sky in a single day. This minimized the problems that hinder wide-field low-frequency mapping. The survey covers the declination ranges of $-50° \leqslant \delta \leqslant +70°$ and is complete in right ascension. The synthesized beam has a resolution of 26′ × 42′ sec ($\delta - 14°.1$). The sensitivity of the survey is 5 Jy/beam (1σ). Special care has been taken to ensure that the antenna responds to structures on all angular scales and the survey is suitable for studying both point and extended sources.

In Fig. 2, we present the 34.5 MHz map of the Vela-Puppis complex made from the observations carried out in January 1987 as a part of the survey. It shows Vela X, Y and Z clearly and another SNR Puppis A (0822 − 43). Vela X has two radio peaks in Fig. 2 corresponding to those seen also in Fig. 1. Similarly, the local minimum between

*This telescope is operated jointly by the Indian Institute of Astrophysics, Bangalore and the Raman Research Institute, Bangalore.

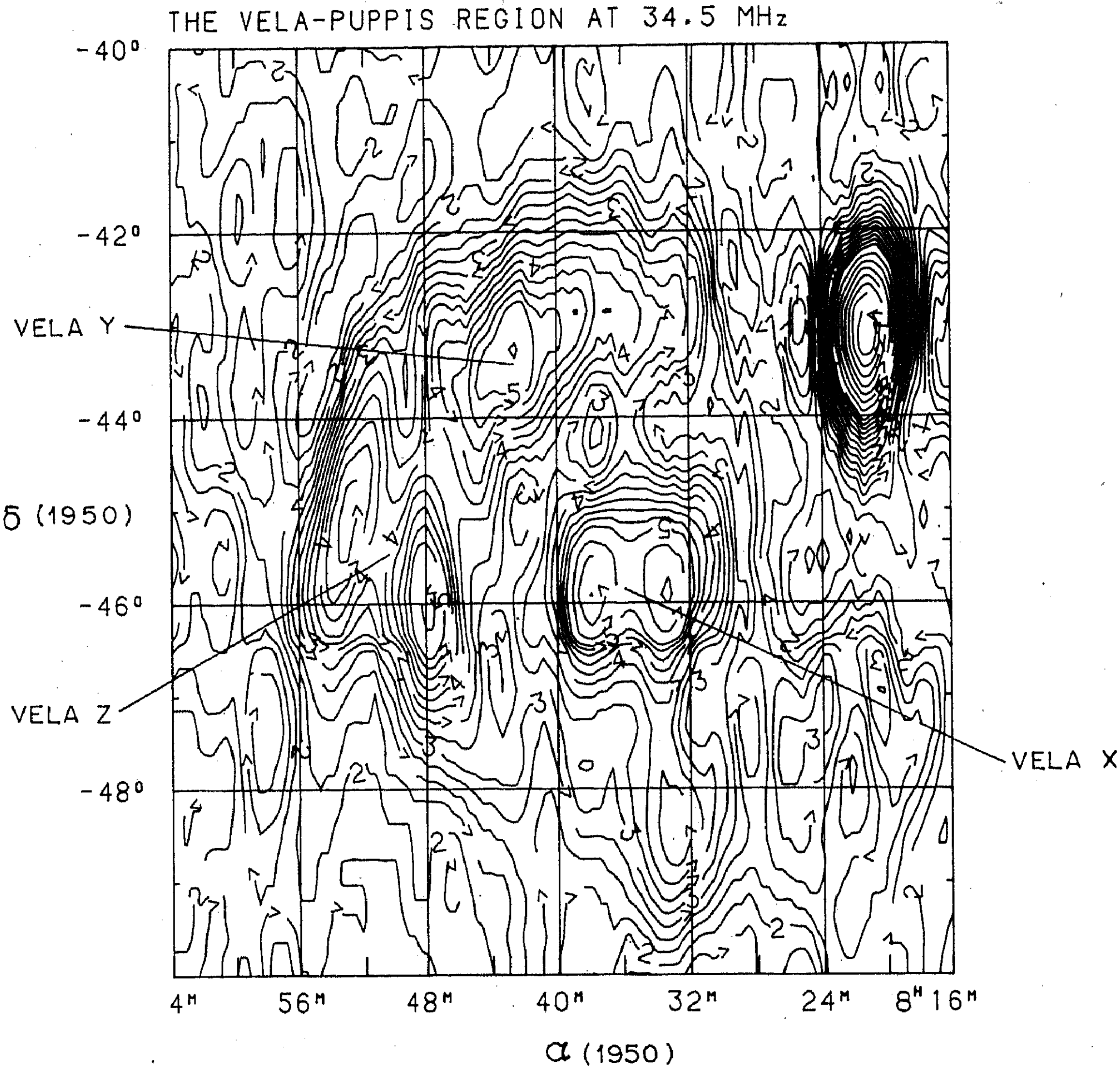


Figure 2. The 34.5-MHz map of the Vela-Puppis region. This has a resolution of 26′ × 84′ along R.A. and Dec. respectively. The contours are labelled in units of 10^4 K.

Vela X and Y can be seen in both maps. Fig. 2 shows two peaks in Vela Z, although this is not obvious in any of the high-frequency maps, only the peak 0848−46 having a corresponding feature at higher frequencies. It may also be noted that the extent of Vela XYZ at 34.5 MHz is larger than that at higher frequencies (compare Figs 1 and 2)—the low-frequency size being more compatible with the soft X-ray map of Harnden *et al.* (1985) and the 8° extent found by Seward (1989). There is no special feature in our map at the position of the Vela pulsar. The source RCW 38 (0858−47) which is seen as a strong emission region in Fig. 1, is seen in Fig. 2 as an absorption dip, as would be expected of an H II region.

4. The flux densities of Vela X and Vela YZ

With a view to determining the spectral indices of the components Vela X and YZ, we have estimated their flux densities separately. As seen in Fig. 2, they are well-separated and hence do not pose a problem. The region over which the integrations were carried out are as follows:

(i) $08^h28^m \leqslant \alpha \leqslant 08^h42^m$; $-47° \leqslant \delta \leqslant -44°$ for Vela X and
(ii) $08^h42^m \leqslant \alpha \leqslant 08^h56^m$; $-48° \leqslant \delta \leqslant -41°$, plus $08^h28^m \leqslant \alpha \leqslant 08^h42^m$; $-44° \leqslant \delta \leqslant -41°$ for Vela YZ.

The baselevel was estimated to be 1.75×10^4 K and the boundary of the integration was 2×10^4 K. The baselevel estimated by averaging the map over $08^h00^m \leqslant \alpha \leqslant 08^h30^m$; $-41° \leqslant \delta \leqslant -35°$ is 1.5×10^4 K. However, the boundaries of Vela imply a baselevel of 2×10^4 K. Thus, we adopted the average value of these for the integrations. Fig. 2 shows this value to be reasonable. The resultant flux densities for Vela X and YZ are 1800 and 3900 Jy respectively. We believe these to be accurate to within 10 per cent based on the errors in similarly estimated flux densities of about 100 southern sources taken from Mills, Slee & Hill (1960) and their repeatability over many days in our observations. The uncertainty in the adopted baselevel (believed to be <10 per cent) is not included in the estimated accuracy of the flux densities. We have estimated the contribution to the estimated flux densities from sources unrelated to Vela XYZ but lying within the region of integration. For this purpose, we have used the Molonglo catalogue of radio sources at 408 MHz (Large *et al.* 1981), the MSH catalogue at 85 MHz (Mills, Slee & Hill 1960) and the 4C catalogue (for possible aliased sources) at 178 MHz (Gower, Scott & Wills 1967). The total contribution of these sources to the integrated flux density of Vela X or YZ is $\leqslant 2$ per cent and this has been subtracted.

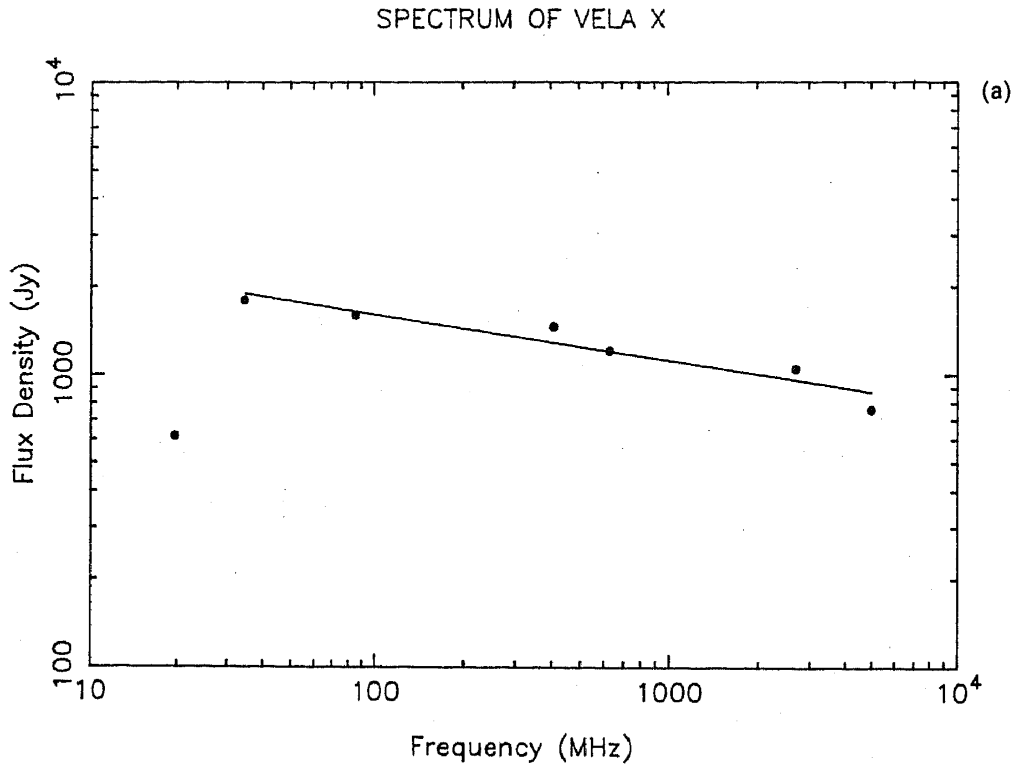
Table 1 lists the flux densities of Vela X and YZ at those frequencies where the estimates are unambiguous. We note that the 19.7-MHz values quoted by Rishbeth

Table 1. Integrated Flux densities of Vela X and YZ.

Frequency (MHz)	Flux density (Jy) Vela X	Vela YZ	Notes
19.7	616	1668	1
34.5	1800	3900	2
85	1600	—	3
408	1466	1633	4
635	1211	1149	5
2700	1050	350	6, 7
5000	759	—	6

Note: All the flux densities are integrated values. However, the values at 19.7 MHz are derived from peak values as described in the text. The errors on the flux densities are typically 10 per cent (1σ). The integrated flux densities of Vela XYZ are 2360 and 1400 Jy at 635 and 2700 MHz respectively (Milne 1968). The integrated flux densities of Vela X at the two frequencies have been subtracted from these to obtain the flux densities of Vela YZ.

1. Estimated from Rishbeth (1958).
2. Present observations.
3. Rishbeth (1958).
4. Estimated from Haslam *et al.* (1982).
5. Estimated from Milne (1968).
6. Milne (1980).
7. Milne (1968).



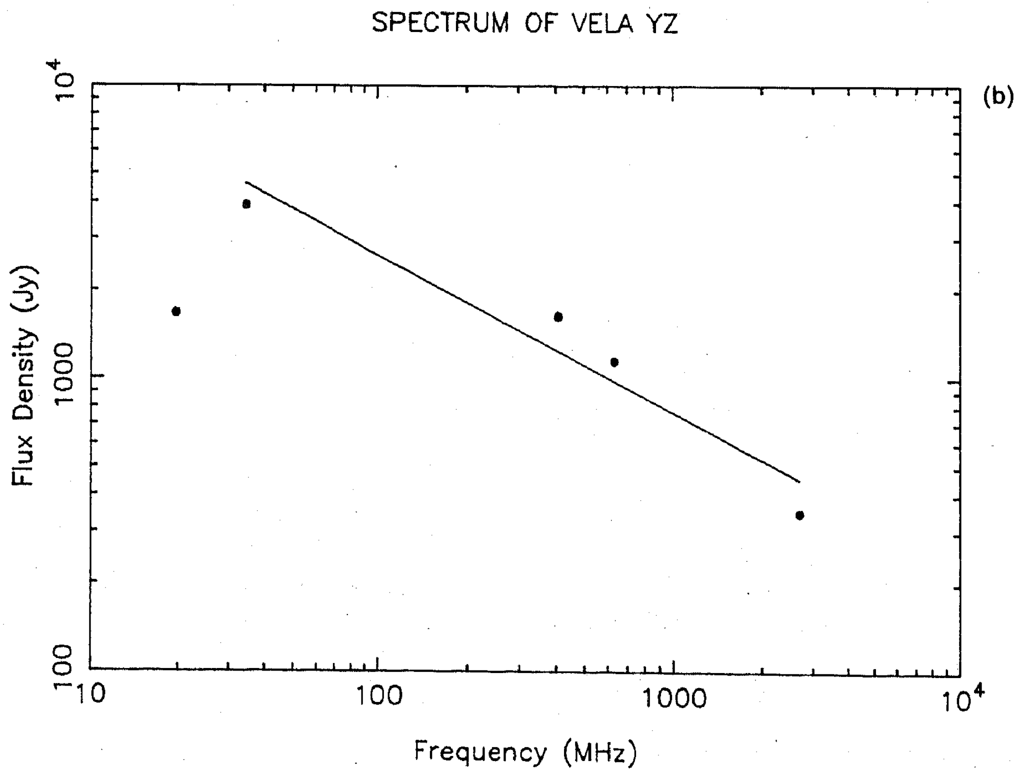


Figure 3. The spectra of the integrated flux densities of Vela X and YZ. Excluding the 19.7-MHz values, the best-fit spectral indices are $\alpha = -0.16 \pm 0.02$ for Vela X and -0.53 ± 0.03 for Vela YZ.

(1958) are peak flux densities. To make an estimate of the corresponding integrated flux densities, the ratios of integrated to peak flux density for Vela X and YZ are needed. For this purpose, we convolved the 34.5-MHz data to the same resolution as the 19.7-MHz observations and estimated the peak flux densities of Vela X and YZ. Since we know the integrated flux densities at 34.5 MHz, the desired ratios can be computed. The corrected 19.7-MHz flux densities obtained using these ratios are given in Table 1. At 635 MHz, Milne (1968) quotes the total flux density for Vela XYZ as 2360 Jy. We have integrated the contour maps of Milne (1968) to estimate the values for Vela X and YZ separately. In addition, we have also integrated the 408-MHz map of Haslam *et al.* (1982) to estimate the flux densities of these two components separately. These are also given in Table 1. Since formal errors are not always available, we assume 10 per cent error on the flux densities in Table 1. Figs 3a and 3b show the spectra of Vela X and YZ respectively. Excluding the 19.7-MHz values, the best fit values for the spectral indices ($S \propto \nu^{\alpha}$) are -0.16 ± 0.02 for Vela X and -0.53 ± 0.03 for Vela YZ. The 19.7-MHz flux densities of Vela X and YZ are significantly

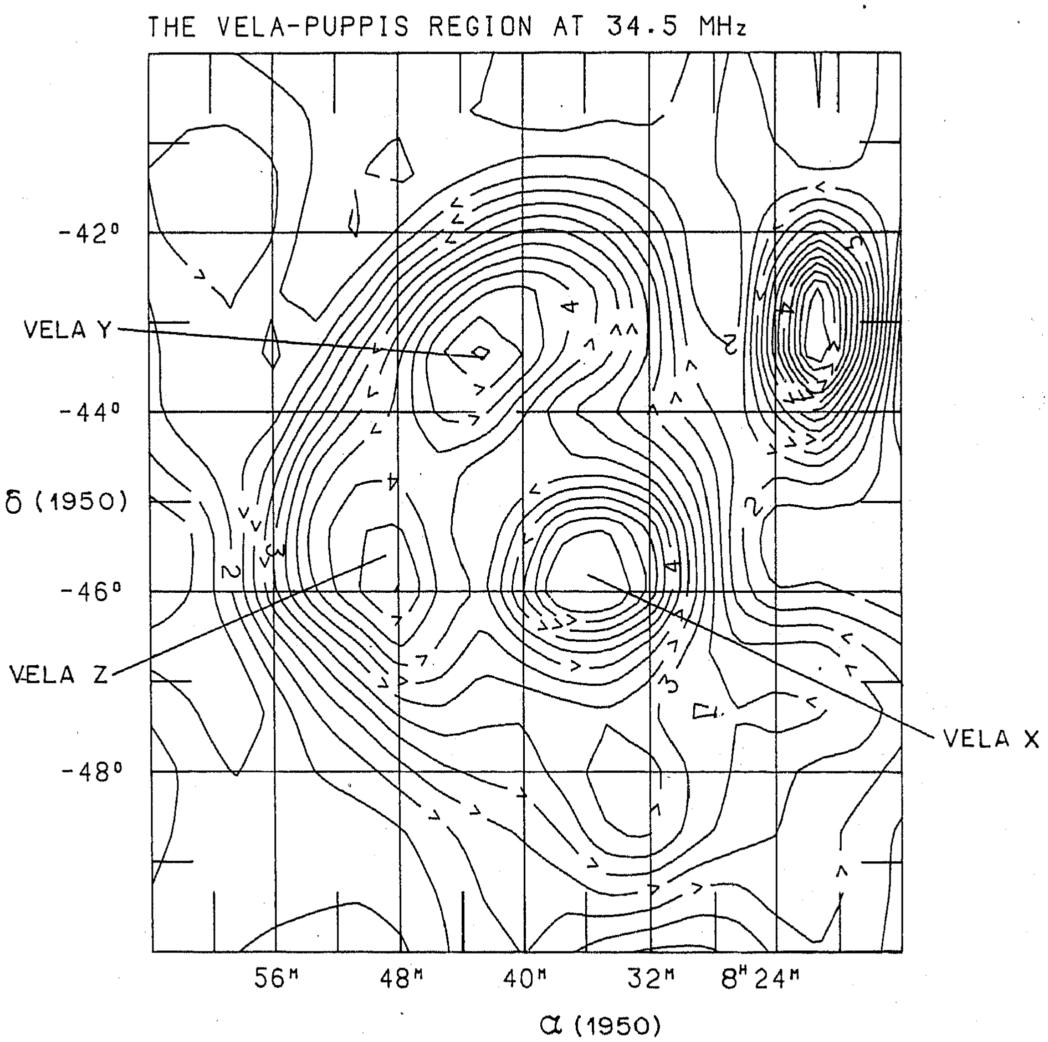


Figure 4. The Vela-Puppis region at 34.5 MHz (*i.e.* Fig. 2), convolved to a resolution of 1° × 1°.5. The contours are labelled in units of 10^4 K.

below their respective values at 19.7 MHz that can be estimated from their high-frequency spectra. This may be due to the free-free absorption of the SNR emission in the intervening gas. An estimate of this absorption is made in Section 6.

5. The spectral-index distribution

To derive the spectral-index distribution across Vela XYZ, we used our 34.5-MHz map and the 408-MHz map of Haslam *et al.* (1982). The original resolution at 408 MHz is 51′ × 51′ while that at 34.5 MHz is 26′ × 84′ at the average zenith angle of Vela XYZ. Before comparison, we convolved both maps to a common resolution of 1° × 1°.5 (Figs 4 and 5). The derived spectral-index distribution is shown in Fig. 6. The

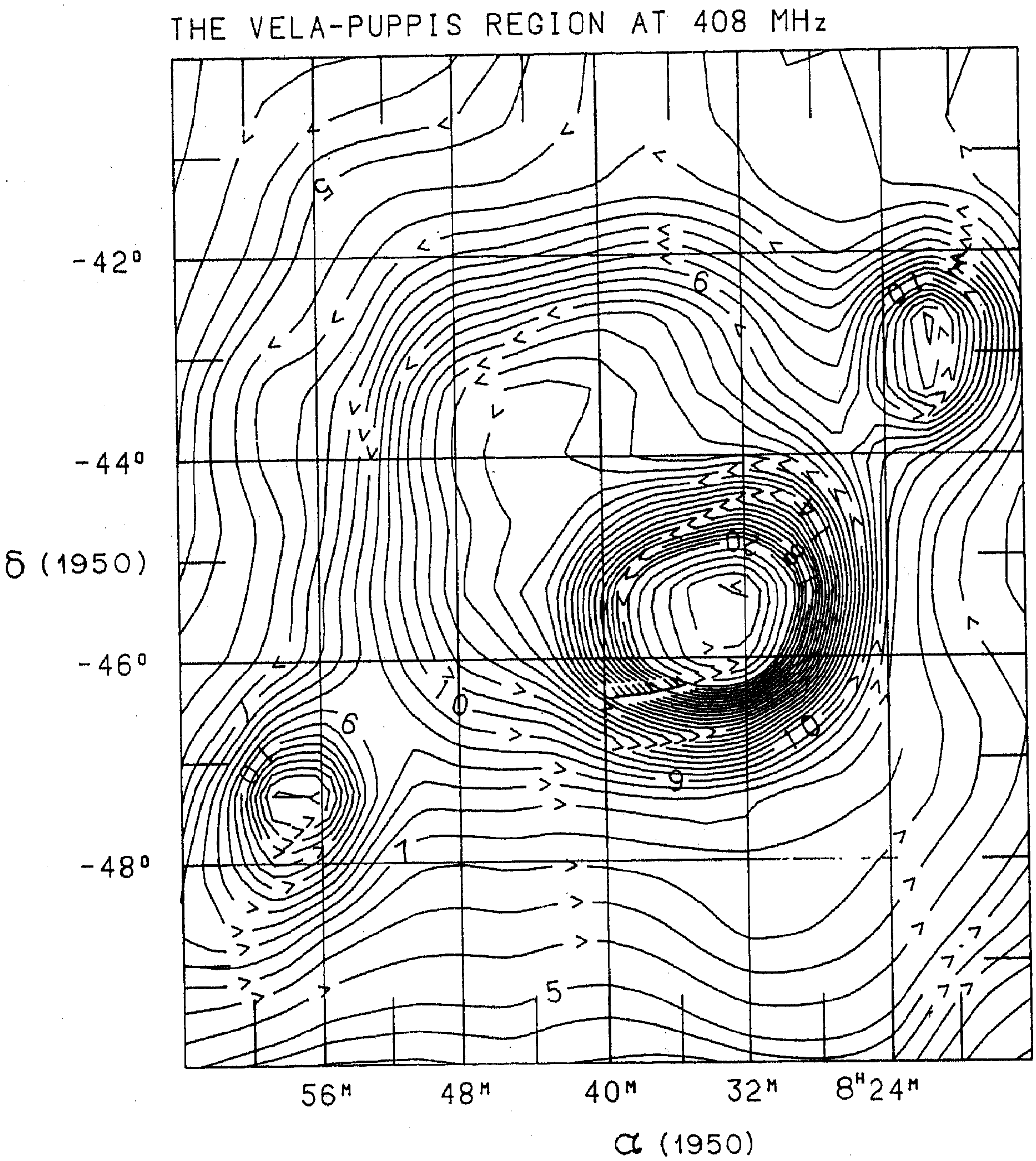


Figure 5. The Vela-Puppis region at 408 MHz, convolved to a resolution of 1° × 1°.5. The original data at a resolution of 51′ × 51′ were taken from Haslam *et al.* (1982). The contours are labelled in units of 10 K.

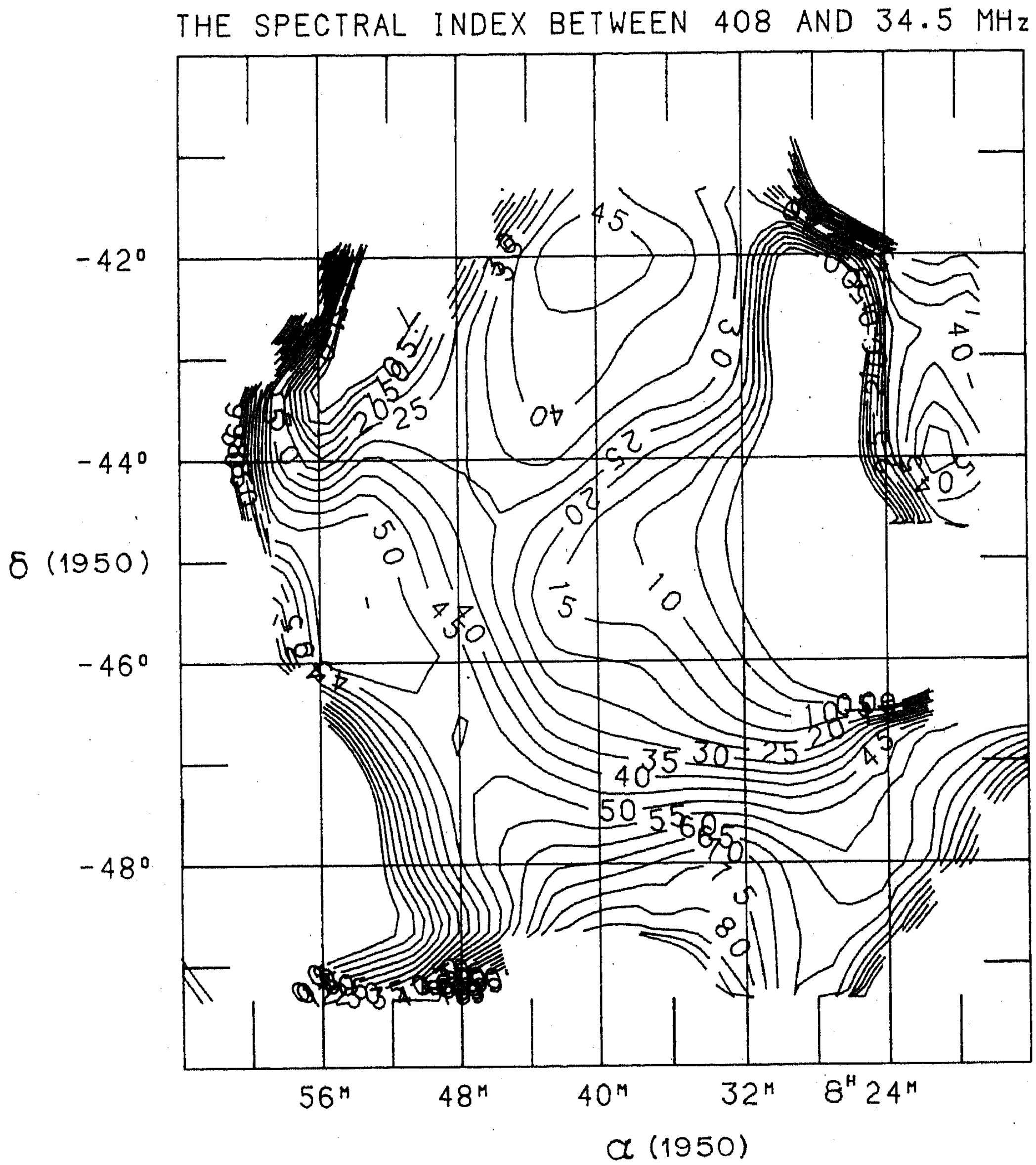


Figure 6. The spectral-index distribution obtained from the maps in Figs 4 and 5. A contour labelled 25 means $\alpha = -0.25$ and similarly for the others. The contours are in steps of 0.05 and the value of α ranges from 0.0 to -0.80. The values towards the edges of the remnant are not significant.

baselevels assumed at 408 and 34.5 MHz to produce this map were 50 K and 1.75×10^4 K, respectively. Fig. 6 shows spectral gradients, but it is clear that most of Vela X has a spectral index of $\alpha \approx -0.1$ while most of Vela Y and Z has $\alpha \approx -0.45$. Puppis A is seen to have $\alpha \approx -0.5$ in agreement with previous estimates (Green 1988 and references therein).

6. Discussion

Two issues that are important in the present context are: (1) whether Vela X is a plerion or merely an enhanced portion of a single shell remnant Vela XYZ, (2) if Vela X *is* a plerion, whether PSR 0833–45 is associated with it. We discuss both these here.

The major justification given by Milne & Manchester (1986) for doubting that Vela X is a pulsar-driven component is that, according to them, its spectral index is similar to the rest of the SNR. Though Weiler & Panagia (1980) estimated the spectral index of Vela X to be -0.08, Milne & Manchester (1986) raised the following objections: (1) the estimate of spectral index by Weiler & Panagia takes into account the values for the integrated flux densities of Vela X at 85 MHz (Rishbeth 1958), 1.44 GHz (Mathewson, Healey & Rome 1962) and 2.7 and 5 GHz (Milne 1980). However, they ignore the measurements made at 408 and 635 MHz by Milne (1968), (2) the spectral-index estimate by Weiler & Panagia is strongly influenced by the 85-MHz value whioh is believed (Milne & Manchester 1986) to be affected by free-free absorption occuring either in the SNR itself or in the Gum Nebula. Based on electron density and temperature estimates for the intervening gas, Milne and Manchester arrived at a free-free optical depth for Vela X of 0.25 at 85 MHz. They proposed that if the 85-MHz flux density of Vela X is corrected for such an absorption then there is no significant difference between the spectral index of the object and the rest of the region, with both equal to -0.35.

The first objection has been taken care of in the present paper, as we have included the 408 and 635 MHz values when estimating the spectral indices. As to the second objection, it does not appear reasonable to propose any significant free-free absorption at 85 MHz. An optical depth of 0.25 at 85 MHz implies optical depths of 1.5 and 5 at 34.5 and 19.7 MHz respectively. Since there is insignificant free-free absorption at, say, 2.7 GHz (where the flux density of Vela X is 1050 Jy, Milne 1980) we derive (assuming $\alpha = -0.35$, Milne & Manchester 1986) expected flux densities of Vela X at 34.5 and 19.7 MHz of 4829 and 5876 Jy respectively. Free-free absorption would reduce these to 1000 and 40 Jy respectively. However, the actual observed values are 1800 and 360 Jy and grossly discrepant with the predicted values on the assumption of free-free absorption such as proposed by Milne & Manchester (1986). The amount of free-free absorption in front of the Vela supernova remnant is estimated by a χ^2 fit to the observed flux densities of Vela X and Vela YZ to the function

$$S_\nu = \frac{2k\nu^2}{c^2}(T_e - T_B)(1 - e^{-\tau})\Omega_{\rm SNR} + S_{\nu,\rm SNR}e^{-\tau}.$$

where S_ν is the observed flux density at a frequency ν, $S_{\nu,\rm SNR}$ is the expected flux density of the SNR, $\Omega_{\rm SNR}$ is the solid angle of the SNR, T_B is the background temperature at this frequency and T_e and τ are the electron temperature and optical depth (at ν) of the gas. The best fit to the flux densities (including the 19.7-MHz values also) of both Vela X and YZ imply $T_e \leqslant 10{,}000$ K and $\tau_{34.5} \approx 0.2$, suggesting a foreground absorption, possibly in the Gum nebula. The effect of this absorption, however, is so small that the spectral indices of Vela X and YZ, obtained including it agree with those obtained excluding it (Section 4), within errors.

We have seen that both the spectral-index distribution and the spectrum of the integrated flux densities imply that Vela X is a flat-spectrum source, while Vela YZ has a spectrum typical of a shell-type SNR. This, along with its other characteristics (see Weiler & Panagia 1980), puts Vela X in the class of plerions while Vela YZ appears to be a typical shell remnant. It is generally believed that plerions are powered by an active pulsar and if Vela X is a plerion, one may ask what its energy source is. Until recently it was accepted that PSR 0833−45 powers Vela X. The fact that the pulsar is about 40′ away from the radio peak of Vela X was attributed to its proper motion. Recently the proper motion of the Vela pulsar has been measured (Bailes *et al.* 1989; Ögelman, Koch-Miramond & Aurière 1989) and this indicates a velocity of about 100 $\mathrm{km\,s^{-1}}$ *in the direction shown by the arrow* in Fig. 1. This rules out an origin for PSR 0833−45 anywhere in the vicinity of the radio peak of Vela X. In addition, PSR 0833−45 is at the northern edge of the extended (hard) X-ray nebula (see Fig. 1). If this emission is energized by the pulsar then this asymmetry, too, is difficult to understand. In this context it may be worth pointing out that a similar asymmetric morphology is seen in the case of CTB 80 (Strom 1987; Wang & Seward 1984). One possibility is that the 'pulsar bubble' has been expanding asymmetrically perhaps due to inhomogeneities in the ambient medium. The other possibility is that the extended X-ray nebula is not non-thermal. Future observations of this remnant by ROSAT should throw some light on this. Both these are worth investigating before invoking another unseen pulsar (a former binary companion of PSR 0833−45?) as responsible for Vela X and the extended X-ray nebula!

The morphology of Vela XYZ and the position of PSR 0833−45 have been accommodated in an alternative picture by Manchester & Durdin (1983) and by Manchester (1987). In this model they propose that for most SNRs there is a biannular enhancement of the shell radio emission and suggest several possible mechanisms for the creation of such an enhancement. All of these mechanisms involve biconical outflows from either the progenitor star or a central compact object. They would like to explain essentially all the observed morphologies of SNRs within this basic model by considering the effects of different opening angles for the biconical flow, different viewing angles, an inhomogeneous interstellar medium and the possible presence of a pulsar-driven nebular component. While this may explain the observed morphologies of SNRs that are like 'blobs', 'loops', 'arcs', etc., there are some basic difficulties with this model as applied to the Vela SNR. In the context of the biannular model, these authors identify the outer (Vela YZ) loop as one ring of enhanced emission and Vela X as a second ring. They point out that these two rings map on to one another through the position of PSR 0833−45. This implies that the radio emission we see from Vela X and YZ is due to particles (electrons) ejected by PSR 0833−45. If so, it is difficult to explain how Vela X and YZ display such very different radio spectra. Even in the general context of SNRs, we feel that the biannular model runs into similar difficulties. There are approximately 150 known SNRs in our Galaxy (Green 1988). These have an average spectral index of -0.47 ± 0.15. Based on their centre-bright appearance in the radio maps let us consider the following six plerionic remnants: G21.5−0.9, G74.9 +1.2, G130.7+3.1, G184.5−5.8, G263.9−3.3, and G326.3−1.8. Their average spectral index turns out to be -0.13 ± 0.1. The probability for a randomly selected set of six remnants to have their spectral index > -0.4 equals 0.1 per cent. It is unlikely that these remnants have come from the same distribution as the rest of the 150 odd remnants. Apart from this, the biannular model will also have to account for the higher degree of linear polarization in the radio emission, the more ordered field in the remnant and the non-thermal X-ray emission found only amongst the plerions. While morphological variety can be attributed to the viewing geometry, it is hard to see how these other characteristics could be accommodated in the biconical model.

As was mentioned in Section 3, the size of Vela XYZ is larger at 34.5 MHz compared to that at higher frequencies (Figs 1 and 2). This is consistent with the note of Seward (1989) who finds an X-ray size of 8° for the SNR with an extension seen towards the south-west. A similar extension is also seen in the 34.5-MHz map. The 408-MHz map of Haslam *et al.* (1982) also shows shell-like emission beyond the high frequency extent of Vela XYZ. If this is the true size of the remnant, then the location of PSR 0833 − 45 and Vela X would be roughly close to the centre of the remnant; in this scenario, the Vela SNR has a hybrid morphology (an outer shell with a central plerion), very similar to G326.3 − 1.8. A highly asymmetric expansion of the 'pulsar bubble' could then account for the pulsar not being near the centre of Vela X. While this scenario looks quite attractive it raises several questions:

1. Does the outer shell, as seen in X-ray and at 408 MHz, define the true extent of the Vela SNR?
2. Why is the shell much less prominent in the 34.5-MHz map towards the north-east compared to that in the 408-MHz map?
3. Is there any evidence to support the hypothesis of a highly asymmetric expansion of the 'pulsar bubble'?
4. Is the 1° X-ray nebula of hard emission non-thermal in nature?

Further observations and studies are necessary to answer these questions.

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