The interaction of the supernova remnant VRO 42.05.01 with its H\(^{\text{I}}\) environment

T. L. Landecker,\(^1\) S. Pineault,\(^2\) D. Routledge\(^3\) and J. F. Vaneldik\(^3\)

\(^1\)Dominion Radio Astrophysical Observatory, National Research Council of Canada, Penticton, B.C. V2A 6K3, Canada
\(^2\)Département de Physique et Observatoire du Mont Mégantic, Université Laval, Québec G1K 7P4, Canada
\(^3\)Electrical Engineering Department, University of Alberta, Edmonton, Alberta T6G 2G7, Canada

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Summary. H\(^{\text{I}}\) observations of a 2\(^{\circ}\)13 field centred on the SNR VRO 42.05.01 (G166.0 + 4.3) are presented with resolution of 2 km s\(^{-1}\) in velocity and 4 arcmin in angle. Full sensitivity to structures of all angular sizes down to this scale is ensured by combining single-antenna and aperture synthesis telescope data. The interaction of the SNR with the surrounding H\(^{\text{I}}\) is seen. The observations support a previous model developed to explain the unusual structure of the SNR; after initial expansion in a warm medium of density \(\sim 1\) cm\(^{-3}\) the blast wave has broken into and re-energized a pre-existing low-density (\(\sim 0.01\) cm\(^{-3}\)) hot cavity. Despite confusion with extraneous H\(^{\text{I}}\) features clearly related to the SNR can be seen. The old interstellar cavity is seen as a prominent hole in the H\(^{\text{I}}\). A hemispherical shell, containing 40 \(M_\odot\) of H\(^{\text{I}}\), expanding at 8 km s\(^{-1}\), is associated with the SNR. A 25-\(M_\odot\) H\(^{\text{I}}\) cloud has been hit by the SNR shock and material is being ablated from it by the post-shock flow. The systemic velocity of the H\(^{\text{I}}\) associated with the SNR is \(\sim 34 \pm 5\) km s\(^{-1}\). A kinematic distance cannot be obtained, but the SNR probably lies in the Perseus spiral arm at a distance of \(4.5 \pm 1.5\) kpc. The field also contains linear H\(^{\text{I}}\) filaments of extent 150 pc in the vicinity of the SNR but unrelated to it; they appear to be aligned with the ambient magnetic field. Measurements of small-diameter continuum sources in the field are presented.

1 Introduction

Supernova remnants (SNRs) act as probes of the interstellar medium. One of the most interesting remnants from this point of view is VRO 42.05.01 (G166.0 + 4.3) which appears to have
encountered a pre-existing interstellar cavity in its expansion. In the absence of the SNR the cavity would be undetectable.

The unusual structure of this SNR was first seen in the radio map of Paper I (Landecker et al. 1982b); Fig. 1 shows the SNR at 1.42 GHz. There are two distinct components of radio emission, the hemispherical 'shell' on the Eastern side and the extended 'wing' to the west. We shall follow the practice of our previous papers, and continue to use the terms shell and wing to refer to these two components. In Paper I we postulated that the expanding shock had encountered an abrupt density discontinuity in the interstellar medium (ISM). Paper II (Pineault et al. 1985) presented optical and radio observations of VRO 42.05.01 and outlined a model for the expansion of the SNR. This model envisaged an explosion and initial expansion within a warm medium of density $n_w = 1 \text{ cm}^{-3}$, followed by the abrupt breaking out of the shock into a hot region of low density, $n_h = 0.01 \text{ cm}^{-3}$. Since breakout the shell component of the SNR has continued to expand in the warm medium. The blast wave has rapidly crossed the hot low-density region, and the bright western edge of the wing has resulted from the shock impinging on denser material on the western boundary of the hot region. The hot region is seen in this model as an interstellar cavity, itself the remnant of one or more previous supernovae or stellar wind bubbles. Paper III (Pineault, Landecker & Routledge 1987) presented radio observations of higher angular resolution and elaborated some of the details of the model of Paper II, in particular the details of the re-energization by the SNR of the hot interstellar cavity.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Map of 1.4-GHz continuum emission from VRO 42.05.01. The synthesized beam is $1.0 \times 1.4 \text{ arcmin}^2$ (EW×NS). Contours of brightness temperature are shown from 0.25 to 2.5 K in steps of 0.25 K. 1 K is equivalent to 8.3 mJy beam area$^{-1}$. 

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Cox & Smith (1974) proposed that hot, low-density cavities in the ISM will be formed by SNRs and they suggested that, given an adequate SN rate, such cavities would join until a network of interconnecting 'tunnels' was formed in the ISM. Smith (1977) elaborated upon this model and studied the injection of energy into the tunnels by subsequent SN events. Our observations of VRO 42.05.01 constitute the first study of this process at work.

In this paper we present H\textsc{i} observations of a field centred on VRO 42.05.01 and examine them with a view to further understanding the interaction of the SNR with the ISM. In Section 2 we describe the observations and in Section 3 present the results obtained in the continuum and the H\textsc{i} line; general H\textsc{i} properties of the field are presented in Section 3.2 and evidence for association of some of this H\textsc{i} with the SNR in Section 3.3. We discuss the distance to the SNR in Section 4.1 and the magnetic field in the vicinity of the SNR in Section 4.2. Gas shocked by the SNR is discussed in Section 4.3 and, finally, in Section 4.4 we compare our observations with previous observations of VRO 42.05.01.

2 Observations

VRO 42.05.01 was observed in the H\textsc{i} line and in the continuum at 1420 MHz with the Synthesis Telescope at the Dominion Radio Astrophysical Observatory in 1982 October. The telescope (Roger et al. 1973) consists of four 9-m antennas and gives complete baseline coverage from 13 to 604 m. The field of view is 2°.13 and angular resolution at the declination of VRO 42.05.01 is 1×1.4 arcmin\(^2\) (EW×NS). H\textsc{i} maps were obtained from 128 channels of the digital cross-correlator covering 85 to −125 km s\(^{-1}\) (all velocities in this paper are relative to the local standard of rest). A continuum map was synthesized from data observed at the same time in a 15-MHz band which is symmetrical about the H\textsc{i} band but excludes it. After subtraction of this continuum map, the H\textsc{i} maps were corrected for the primary polar diagram of the antennas using a Gaussian function 105 arcmin FWHM.

H\textsc{i} data for baselines shorter than 13 m were obtained from measurements made with the DRAO 26-m telescope. The combination of Synthesis Telescope and single-antenna data has resulted in complete coverage of the $u-v$ plane. Galactic H\textsc{i} emission in general fills the field of view of the telescope, and image processing techniques (such as CLEAN) cannot be used for image restoration; complete coverage of the $u-v$ plane, including baselines down to zero, is the only way to make accurate maps of galactic H\textsc{i} under these circumstances (for elaboration of this points see Section 4.4 below).

In addition to the H\textsc{i} data, some continuum data for small-diameter sources in the field are presented. Results from two separate continuum observations, made in 1981 November and 1982 October, were combined for this purpose (for details of these observations see table 1 of Paper III).

3 Results

3.1 Continuum

Fig. 1 shows the continuum emission from VRO 42.05.01 at 1.42 GHz; maps from the two continuum observations mentioned above were combined to produce this figure. The noise level is lower than that of our previous maps, allowing the faint extremities of the wing component to be seen more clearly. Table 1 lists those small-diameter sources in the 2′13 square field centred on VRO 42.05.01 whose flux densities exceed 25 mJy (it is complete to this level) as well as some weaker sources of special interest, mostly those seen within or near the boundaries of the SNR. The tabulated flux densities and sizes are those of best-fitting Gaussians and the flux density scale was tied to that of Baars et al. (1977) through calibration
Table 1. Small-diameter sources in the field of VRO 42.05.01.

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<tr>
<th>No.</th>
<th>Right ascension (1950)</th>
<th>Declination (1950)</th>
<th>Flux density (mJy)</th>
<th>Size (arcmin)</th>
<th>Position angle (degrees)</th>
<th>Comments</th>
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<td>5h 17m 14:5 ± 0.2&quot;</td>
<td>43° 13' 57&quot; ± 2&quot;</td>
<td>42 ± 4</td>
<td>1.0 x 0.2</td>
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<tr>
<td>2</td>
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<td>0.9 x 0.2</td>
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<tr>
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<td>42 49 36 ± 2</td>
<td></td>
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<td>9P21 (ref. 1)</td>
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<tr>
<td>6</td>
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<td>42 41 06 ± 2</td>
<td>98 ± 6</td>
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<td>7</td>
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<td>42 10 07 ± 2</td>
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<tr>
<td>20</td>
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<td>In SNR linear filament</td>
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<tr>
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<tr>
<td>21b</td>
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<td>60 ± 4</td>
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<td>75 ± 3</td>
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<td>61 ± 3</td>
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<td>368 ± 16</td>
<td>1.6 ± 0.3</td>
<td>25</td>
<td>4C + 43.12 (ref. 3)</td>
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References: 1. Routledge et al. (1986); 2. Brundage et al. (1971); 3. Gower et al. (1967).
observations of 3C147. Sources from Table 1 should be referred to as 13 Pn where \( n \) is the serial number in the table. The counts of Willis et al. (1977) predict 7.6 extragalactic sources in the 4.55 square degree map area with flux density \( S > 100 \) mJy, and 17 sources with \( S > 50 \) mJy. Actual numbers from Table 1 are 8 and 15 sources, respectively, and we conclude that most or perhaps all of the sources in Table 1 are extragalactic.

3.2 H\(_1\) emission

Fig. 2 shows the average spectrum of H\(_1\) emission over the 128-arcmin field. The observations cover more than the range of galactic velocities, and this spectrum is typical of this general direction (e.g. Weaver & Williams 1973). The emission which dominates the spectrum of Fig. 2 between \(-10\) and \(-30 \) km \( s^{-1} \) is usually associated with the Perseus spiral arm of the galaxy (e.g. Henderson, Jackson & Kerr 1982).

Fig. 3 shows maps of total H\(_1\) emission in the field (maps of total emission are those which include data from baselines from zero out to some resolution limit). The data have been smoothed to a velocity resolution of 4.9 km \( s^{-1} \) (by averaging three single-channel maps) and then smoothed to an angular resolution of 4 arcmin. Each map has had a baseline subtracted equal to the average H\(_1\) level in the field in that velocity range. This does not distort the H\(_1\) structure in the maps, but simply reduces the dynamic range required for their display. The amount subtracted from each map can be read off the spectrum of Fig. 2. The continuum map, observed at the same time, has been subtracted from the line data of Fig. 3, so that, apart from any absorption effects, only H\(_1\) emission is displayed. The peak continuum brightness of the SNR is \( \sim 2.5 \) K, and absorption will therefore be difficult to detect in the presence of H\(_1\) emission of up to 50 K. Each map is labelled with its central velocity, and has superimposed on it a single contour of continuum emission (at full angular resolution) chosen to show the outline of the SNR. Individual H\(_1\) features in the maps are labelled A, B, \textit{et seq.}, and will be discussed.

Figure 2. The average H\(_1\) spectrum over the 128 \( \times \) 128 arcmin\(^2\) field centred on VRO 42.05.01 computed from maps incorporating data from all baselines from 0 to 604 m.
in turn. Most of the H\textsc{i} in the field, as can be expected, has no connection with the SNR but it does tell us something about the environment in which the supernova occurred. Those H\textsc{i} features which we consider to be related to VRO 42.05.01 are discussed in Section 3.3.

At positive velocities the emission is low-level and diffuse; this is presumably local gas, and one would expect to see a predominantly broad, smooth structure. Most of the features evident in this velocity range reach to the edges of the field and probably extend beyond it.

Feature A is a bright emission region which first appears at $+4.7$ km s$^{-1}$ on the western edge of the field and peaks in brightness at $-0.2$ km s$^{-1}$. B appears on the eastern edge at $-5.2$ km s$^{-1}$. A lower-level ridge of emission joins A and B and lies over the SNR; this ridge is evident from about $+9.7$ to $-5.2$ km s$^{-1}$. At $-10.1$ km s$^{-1}$ smaller features begin to appear, and the field contains much detail over the whole range $-10.1$ to $-39.8$ km s$^{-1}$. A, on the western edge, has, by $-10.1$ km s$^{-1}$, blended with C. Bright emission appears at this location right through to $-29.9$ km s$^{-1}$, and is probably the blend of several individual H\textsc{i} structures. We continue, somewhat arbitrarily, to label it C.

From $-15.1$ to $-34.8$ km s$^{-1}$ two trends in the H\textsc{i} are discernible. First, the concentration of emission moves gradually from the southwestern corner of the field across the centre to the northeastern corner, that is, from lower to higher galactic latitude. The Perseus arm, at least in this field, has roughly the appearance of a slab inclined to the line-of-sight; this effect may be part of the general warp of the outer galaxy (Henderson et al. 1982). Second, we note that in this velocity range the H\textsc{i} shows many structures elongated diagonally across the field of view. The direction of their elongation is from south-east to north-west, and is aligned with the bright continuum emission of the shell and wing components of the SNR. It is also parallel to the galactic plane, which, however, lies 4.5$^\circ$ from the centre of the field. The elongated H\textsc{i} features are shown clearly in Fig. 4, which displays two maps, at $-20.0$ and $-24.9$ km s$^{-1}$, made with data from baselines greater than 13 m in order to suppress broad structure and emphasize fine structure. The extent of the diagonal H\textsc{i} structures is striking; we discuss these features further in Section 4.2.

The range $-15.1$ to $-34.8$ km s$^{-1}$ covers the peak and the further side of the main H\textsc{i} concentration (see Fig. 2). At $-15.1$ km s$^{-1}$ D becomes strong; this is a bright feature which lies over the SNR and blends with C. At $-20.0$ km s$^{-1}$ D shows a complex structure, lying over the SNR, and extending beyond its boundaries; D corresponds to an infrared feature visible in the IRAS data (R. Arendt, private communication). D blends into E at $-24.9$ km s$^{-1}$; E is a strongly elongated feature to the south-east of the SNR, which ends more or less at the edge of the SNR.

At $-24.9$ km s$^{-1}$ there is a crescent-shaped structure in the H\textsc{i} coincident with the SNR (we have not labelled it in the map of Fig. 3 to avoid obscuring it). A depression lies over the centre of the SNR and ridges of H\textsc{i} emission are seen roughly superimposed on the two prominent radio emission regions at the edges of the remnant. This H\textsc{i} crescent blends with E in the south-east.

There are other small-scale structures, F, G, H and I, at $-24.9$ km s$^{-1}$, which are probably unrelated to the SNR. At $-29.9$ km s$^{-1}$ C in the south-west persists but D, E, F, G, H and I blend into a large confused structure around the outside of the map. However, a deep hole remains centred on the SNR (Feature J). It is elongated, with the same orientation as the dominant structure of the SNR.

At $-34.8$ km s$^{-1}$ the emission is becoming weaker, and is concentrated to the north-east corner of the field. J is still evident as a region of low emission centred on the SNR; from the minimum of Feature J the intensity of the emission rises in all directions. At $-39.8$ km s$^{-1}$, and at higher negative velocities, there is fairly uniform low-level emission over the whole field. At $-44.7$ km s$^{-1}$, Feature K is seen. It is a small bright patch which lies on the wing component of the SNR over the minimum of Feature J.
Figure 3. Maps of the total H\textsc{i} emission in the direction of VRO 42.05.01. Angular resolution is 4 arcmin and velocity resolution is 4.9 km s\textsuperscript{-1}. Each map has had a constant subtracted equal to the average level of H\textsc{i} in the field at the corresponding velocity. The value subtracted from each map can be read from the spectrum of Fig. 2. There are five levels of grey-scale, −10, −5, 0, 5 and 10 K with black corresponding to maximum brightness. On each map, a single contour represents the continuum outline of the SNR. Equatorial coordinates (epoch 1950) are shown by the grid on each map, and each map is labelled with its velocity.
Figure 4. Maps of H I emission at $-20.0$ and $-24.9$ km s$^{-1}$ made using baselines 13–604 m only in order to emphasize fine structure. Angular resolution is 4 arcmin. Data presentation resembles that of Fig. 3 except that no average value has been subtracted. Grey-scale levels are $-7.2$ to $+7.2$ K in steps of 2.4 K.

Outside the velocity range of the maps of Fig. 3 there are no large emission features. Maps made with data from spacings $>13$ m were, however, examined for small-scale structure. Apart from the structures already described, only one other feature was found near the SNR. This is a small faint patch of emission centred at $+31.1$ km s$^{-1}$ which appears within the boundaries of the shell component; it is shown in Fig. 5 and has no morphological or kinematic features which suggest association with VRO 42.05.01.

3.3 H I FEATURES RELATED TO VRO 42.05.01

In this section we will attempt to judge which H I features are related to the SNR, and will examine some of them in greater detail. The H I crescent seen at $-24.9$ km s$^{-1}$ is coincident with the SNR, and in our opinion is associated with it. We also consider that Feature J, the minimum in the emission centred on the SNR, is related. Feature K, the small patch of emission which lies over the central region of the SNR, is, in our view, also related. In the following paragraphs, we justify these statements.

Fig. 6 gives a more detailed view of the H I in the range of velocities $-22$ to $-54$ km s$^{-1}$ in which we most clearly see features associated with the SNR. This series of maps has a velocity resolution of 2 km s$^{-1}$ and an angular resolution of 4 arcmin, and covers the central 64 arcmin
of the observed field. The data presentation is similar to that in Fig. 3, except that the grey-scale steps are finer and have been chosen to emphasize certain features in the H i. Details are given in the figure caption.

The deep minimum over the SNR (J in Fig. 3) is clearly evident at $-26$, $-28$ and $-30$ km s$^{-1}$. It is elongated towards the north-west, roughly aligned with the wing component of the SNR. We identify this minimum with the interstellar cavity which the SNR has re-energized. However, we note that the H i brightness at the centre of J is never less than 15 K, indicating that confusing H i emission is present. A ‘hole’ over the SNR persists from $-32$ to $-40$ km s$^{-1}$. Over this range the semi-circular arc defined by the continuum shell appears to be completed by an H i feature, seen most clearly at $-38$ km s$^{-1}$. Although there is considerable confusing emission, the diameter of the shell appears to increase towards more negative velocities. This suggests that we are seeing an expanding H i shell. Such a model is illustrated in Fig. 7; the fit shown there yields a systemic velocity of $-38$ km s$^{-1}$, an expansion velocity of 8 km s$^{-1}$, and a radius of 11 arcmin, somewhat smaller than the radius of the semi-circular continuum shell. We also note that the shell is incomplete; an approaching component, expected between $-40$ and $-50$ km s$^{-1}$, is not seen.

From $-34$ to $-40$ km s$^{-1}$ the northern part of the wing is seen outlined by H i. This effect cannot be attributed to absorption of continuum emission. The depression in H i brightness at $-36$ km s$^{-1}$ is about 4 K; the continuum brightness temperature in this region is less than 0.5 K. At $-36$ km s$^{-1}$ there is a remarkably strong resemblance between the hole in the H i and the continuum boundary of the SNR, especially around the north of the shell and the wing.

We shall attempt to estimate the systemic velocity of the SNR from the velocities of the H i features associated with it. There are three possible approaches to this problem. First, we might look for the deepest minimum in the H i hole which we have identified with the interstellar cavity; this gives a value of $-28$ km s$^{-1}$. Second, we might choose the velocity where the hole in the H i has the largest extent and most closely resembles the overall structure of the shell and the wing components together; this leads to an estimate of $-36$ km s$^{-1}$. Finally, our expanding shell model suggests a systemic velocity of $-38$ km s$^{-1}$. These estimates are close to one another, considering that turbulent velocities are $\sim 10$ km s$^{-1}$, and we simply average the three values to obtain a systemic velocity of $-34$ km s$^{-1}$; we assign an error of $\pm 5$ km s$^{-1}$ to this estimate. Turbulence and confusion together limit our ability to determine the systemic velocity of the SNR with greater precision.
Figure 6. A detailed presentation of total H\textsubscript{I} emission in the vicinity of VRO 42.05.01. Data presentation resembles that of Fig. 3 except that a smaller field is shown. Angular resolution is 4 arcmin and velocity resolution is 2 km s\textsuperscript{-1}. The grey-scale step is 2 K and white contours extend the grey-scale where the emission is strongest.
The maps of Fig. 6 show further details of Feature K. Its strongest emission is at $-42$ and $-44$ km s$^{-1}$. It lies over the deep minimum of Feature J, suggesting that it may be accelerated gas associated with the cavity. This interpretation is supported by other evidence in Fig. 6. As we proceed from $-44$ km s$^{-1}$ to more negative velocities, the peak of the emission gradually moves away from the centre of the SNR towards the edge of the wing in the south-west, and the feature gradually splits in two and becomes weaker. We interpret K as a cloud of H\textsc{i} which has been overtaken by the shock and is being torn apart by the post-shock flow. It is significant that the higher velocity parts of the cloud are displaced from the main body of the cloud in a direction away from the centre of the SNR. The highest velocity parts of the cloud (at $-52$ km s$^{-1}$) lie just behind the outer edge of the wing and do not extend beyond it. We discuss this shock-accelerated gas in Section 4.3.

We regard these observations as strong evidence of the interaction of the SNR with its H\textsc{i} environs. We have seen the interstellar cavity which the SNR has re-energized, and we have seen H\textsc{i} which has been accelerated in this process. Between $-26$ and $-40$ km s$^{-1}$ there are

Figure 7. An expanding shell model which appears to fit the H\textsc{i} data between $-32$ and $-38$ km s$^{-1}$. The radius of the shell is about 11 arcmin, somewhat smaller than the radius of the semi-circular arc of continuum emission. The observer views the shell from the right in this diagram, and at each velocity sees a ring of H\textsc{i}. Only the receding half of the shell is seen. The expected diameter of each ring is shown; the lower part of the diagram shows four H\textsc{i} maps, at the indicated velocities, reproduced from Fig. 6.

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unmistakable resemblances between the H\textsc{i} and continuum structures of the SNR. We have concluded that the systemic velocity of the SNR is approximately $-34 \pm 5$ km s\textsuperscript{-1}.

4 Discussion

4.1 The Distance to VRO 42.05.01

We might hope to deduce the distance to VRO 42.05.01 from the velocity of the H\textsc{i} associated with it. We can see from the spectrum of Fig. 2 that the observed velocity of $\sim -34$ km s\textsuperscript{-1} apparently places the SNR on the far side of the major concentration of H\textsc{i} in this direction, which is the Perseus spiral arm. However, considering that random velocities are $\sim 10$ km s\textsuperscript{-1}, it is quite probable that the SNR is within the arm. The question then becomes: how far away is the Perseus arm? Because of the proximity of this direction to the anticentre there are large errors in any kinematic distance. Furthermore, it is well established that the Perseus arm is strongly affected by a density wave shock (Roberts 1972) which causes a discontinuity in the velocity–distance relationship. Fig. 8 shows an approximate kinematic distance curve based on

![Figure 8](https://example.com/figure8.png)

**Figure 8.** Approximate rotation curves for $l = 166^\circ$, based on the Schmidt model and the two-arm spiral shock (TASS) model by Roberts (1972).
Roberts's two-arm spiral shock (TASS) model. This curve has been derived from his 12-degree TASS model by averaging data from his figs 3 and 5 which refer to longitude ranges 130–140° and 185–195° respectively; the mean should apply to the region around $l = 165°$. [We note that Roberts's TASS model has been used in a similar way by Greisen & Lockman (1979) and by Albinson et al. (1986).] It is clear from Fig. 8 that there are great departures from the Schmidt model, and indeed from any smooth rotation curve, and that there is velocity crowding around $-30$ km s$^{-1}$; velocities more negative than $-25$ km s$^{-1}$ correspond to almost any distance from 2 kpc upwards.

We must therefore fall back on indicators that are independent of rotation curves for a distance to the Perseus arm in this direction. H II regions are suitable tracers of spiral structure whose distances can be independently determined if their exciting stars are identified. Georgelin & Georgelin (1976) place the arm at a distance of 2.8 kpc on the basis of a combination of radio and optical estimates of distances to H II regions. However, the 'arm' identified by these authors is defined mostly by objects between $l = 70°$ and $140°$, and is largely undefined at the longitude of interest to us. Blitz, Fich & Stark (1982) list radial velocities of CO associated with H II regions in the outer galaxy, together with the distances to them determined from observations of their exciting stars. Selecting those H II regions from their list which are closest to $l = 166°$ (S212, S217, S219 and S231) we find velocities of $-18$ to $-35$ km s$^{-1}$ corresponding to distances of 2.3 to 6.0 kpc. There is no significant correlation of velocity with distance among these four objects. On the other hand, the CO study by Blitz et al. (1982) taken together with optically derived distances has been interpreted (Fich & Blitz 1984) as implying a rotation curve for the outer galaxy which is flat, or even rising with galactocentric distance. Interpretation of large-scale HI surveys using such rotation curves places the HI of the Perseus arm at about 5 kpc from the Sun (Henderson et al. 1982; Kulkarni, Blitz & Heiles 1982).

We conclude that the best distance estimate to the Perseus arm at $l = 166°$, and so to VRO 42.05.01, is about $4.5$ kpc, but we must place errors of $\pm 1.5$ kpc on this value. We note that surface brightness–diameter ($\Sigma - D$) considerations led us to a distance estimate of $\sim 5$ kpc (Paper I). Since our new value is not significantly different from this we will not revise the estimates of physical parameters in the SNR which we derived in Papers II and III.

It is interesting that the SNR OA184 (G166.2 + 2.5), which lies a few degrees south of VRO 42.05.01, must have a very similar distance. Routledge, Landecker & Vanelidik (1986) find that OA184 has an associated shell of HI whose systemic velocity is $-30$ km s$^{-1}$, very close to the systemic velocity we have assigned to VRO 42.05.01. On the basis of the arguments presented above, we propose a revision to $4.5 \pm 1.5$ kpc for the distance to OA184 from the value of $8 \pm 2$ kpc given by Routledge et al. (1986). The proximity of the two SNRs on the sky may be no more than a coincidence, but it is possible that they are associated in some way. Perhaps the progenitors of both SNRs were stars from the same stellar group. The angular distance between the centres of the two SNRs is $1°8$, while the extent of each is $\sim 1°$. The distance between OA184 and VRO 42.05.01 is at least 140 pc, giving a distance to the SNRs of 4.5 kpc. This exceeds the dimensions of most open clusters or young stellar associations, but it is not unusual for such groups to be dispersed over time (Mihalas & Binney 1981). A velocity differential of 10 km s$^{-1}$ will separate two stars by $150$ pc in $1.5 \times 10^7$ yr, approximately the lifetime of massive stars.

4.2 THE MAGNETIC FIELD IN THE VICINITY OF VRO 42.05.01

Feature J, the hole in the emission seen in Figs 3 and 6 from $-25$ to $-35$ km s$^{-1}$, lies within the wing component of the SNR, where our model of Papers II and III suggests that the SNR is
expanding into the hot interstellar cavity, and we identify this H\textsc{i} feature with the cavity. At $-26$ to $-30$ km s$^{-1}$ the hole seems to extend beyond the SNR to the north-west. The continuum appearance suggests that the interstellar cavity had this elongated shape before the blast wave broke into it. Cox & Smith (1974), in their discussion of hot interstellar cavities, postulated that such structures will be gradually deformed by the tendency of magnetic flux tubes in the walls to straighten.

We take the radio continuum appearance of the SNR, in particular the alignment of the brightest emission regions, as a strong indicator that the ambient magnetic field in the region of the SNR is aligned south-east to north-west. This is basically in accord with the van der Laan (1962) model of SNR radio emission as the product of the interaction of SNR-produced relativistic electrons with a compressed ambient field. Alignment of SNR structure parallel to the galactic plane has been considered as evidence supporting this hypothesis (Caswell 1977; Shaver 1969) and Caswell & Lerche (1979) find further supporting evidence in statistical studies of SNRs. The van der Laan theory has recently been modified by Blandford & Cowie (1982) to apply to a multi-component interstellar medium.

The maps of Fig. 4 provide strong evidence that H\textsc{i} structures are also aligned with the ambient field. We see H\textsc{i} features over the velocity range $-15$ to $-25$ km s$^{-1}$ which are apparently aligned south-east to north-west (Figs 3 and 4). The diagonal H\textsc{i} features to the south-east of the SNR persist to about $-40$ km s$^{-1}$ and Feature K is seen superimposed on a long diagonal filament at $-44.7$ km s$^{-1}$ (Fig. 3). We must point out, however, that the maps of Fig. 4 emphasize fine structure by suppressing broad structure; the maps of Fig. 3 give the only accurate picture of the total H\textsc{i}. It may be that only part of the H\textsc{i} has become aligned with the field. On the other hand, the diagonal filaments may be distinct features, hidden in the total maps by entirely separate broad H\textsc{i} emission. These linear filaments of H\textsc{i} extend to the edges of the field; assuming that they are at the same distance as the SNR (4.5 kpc) they must be at least 150 pc long. Linear H\textsc{i} features such as those seen in this field are common features of the interstellar medium when viewed with arcminute resolution. They have been seen in a number of fields observed with the DRAO Synthesis Telescope (e.g. Landecker, Roger & Higgs 1980; Landecker, Roger & Dewdney 1982a). For the first time we now have evidence that these structures are aligned with the local magnetic field. The mechanism of alignment probably involves interaction of neutral material with ionized gas to which the magnetic field is attached. Similar alignments have been seen on larger scales, especially near the North Polar Spur (for a review, see Heiles 1987).

### 4.3 The Post-shock H\textsc{i}

In this section we discuss in greater detail the two structures in the H\textsc{i} which have been affected by the SNR shock. They are: (i) the expanding half-shell seen from $-34$ to $-40$ km s$^{-1}$ and (ii) Feature K, seen from $-42$ to $-52$ km s$^{-1}$.

The expanding shell is depicted in Fig. 7. We estimate that the shell thickness is 0.2 of its radius and that half of a spherical shell is present. Assuming a distance of 4.5 kpc to the SNR, the mass of H\textsc{i} in the shell is roughly 40 $M_\odot$. The radius of this H\textsc{i} shell is slightly smaller than that of the continuum shell, and we surmise that the two are related, although their exact spatial relationship is not clear. It remains difficult to understand why we see a complete circular H\textsc{i} shell at $-38$ km s$^{-1}$ (Fig. 6) while only a semi-circle of continuum emission is seen. It is, however, plausible to find a shell of swept-up H\textsc{i} behind the shock front, which we believe to be in its isothermal phase (Paper III). If the material in this H\textsc{i} shell has been swept up from the interior of the shell component of the SNR, then the initial density was $\sim 0.1$ cm$^{-3}$. This is about one tenth the density assumed in the model developed in our previous work (Papers II

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and III), although we must emphasize that our estimate of the mass of H\textsc{i} in the shell is very approximate because of the confusion. Furthermore, a considerable fraction of the swept-up material may still be ionized and therefore undetected in the present observation. We are seeing the receding half of a spherical shell of H\textsc{i} between $-32$ and $-38$ km s$^{-1}$; we do not see its approaching counterpart between $-40$ and $-50$ km s$^{-1}$. In that velocity range we see Feature K.

The structure of Feature K suggests it is a cloud struck by a shock. The bulk of the gas is at $-43$ km s$^{-1}$, and parts of the cloud have been accelerated to velocities as high as $-52$ km s$^{-1}$ and have moved away from the main cloud towards the edge of the wing in the south-west; Fig. 9 shows the location of H\textsc{i} features at two velocities. The mass of Feature K is $\sim 25 M_\odot$; about 15 per cent of this gas has apparently been ablated.

Can the velocity difference between the bulk of the H\textsc{i} and the ablated gas explain the apparent position difference? The shift in position between $-43$ and $-52$ km s$^{-1}$ is approximately 8 arcmin. At a distance of 4.5 kpc this is equivalent to an actual distance of 10 pc. The age of the SNR determined in Paper III is 81 000 yr, and the time since breakout is $\sim 78$ 000 yr. If we assume that the acceleration process has been underway for about 80 000 yr, then the actual velocity difference must be $\sim 100$ km s$^{-1}$, some 10 times larger than the observed offset of 9 km s$^{-1}$ (see Paper III for a discussion of errors in these time estimates). If this is so, then the direction of acceleration must lie nearly in the plane of the sky, so that we see only a small radial component of the actual velocity offset. We should not be surprised to see gas which has been accelerated across the line-of-sight, for this is just the gas whose optical depth along the line-of-sight will be enhanced by compression, rendering it easily detectable. Feature K is probably a piece of the western wall of the cavity, hit after the shock has crossed the cavity, but it is not really important whether it is viewed as a piece of the wall accelerated to a higher than average velocity, or as a separate cloud.

In Paper III we estimated that material velocities in the cavity were $\sim 1400$ km s$^{-1}$ at breakout, and have decreased to $\sim 400$ km s$^{-1}$ now. These velocities can easily account for the observed magnitude of the velocity differential (100 km s$^{-1}$). In the model by McKee, Cowie &

**Figure 9.** Map showing the locations of H\textsc{i} features (cross-hatching) at two velocities relative to the continuum emission from the SNR (single contour). The H\textsc{i} data is taken from the maps shown in Fig. 6. At $-44$ km s$^{-1}$, H\textsc{i} emission above 4 K is shown; at $-52$ km s$^{-1}$ the minimum level is 2 K. The progressive shift to the west as the velocity becomes more negative is interpreted as evidence of ablation of gas from the main cloud at $-42$ to $-44$ km s$^{-1}$.

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Ostriker (1978) a cloud is accelerated by the secondary shock that passes through the cloud after it is overtaken by the blast wave, and is then further accelerated by the smooth flow of shocked intercloud material past the cloud. Velocities well above that of the secondary shock can be produced. On the other hand, Nittmann, Falle & Gaskell (1982) have argued that only the impulsive phase of acceleration occurs, so that the ultimate cloud velocity is of the order of the velocity of the secondary shock, and no more. Even in this case the calculations of Paper III (in particular the model evolutionary history of table 3) show that velocity differentials of $\sim 100$ km s$^{-1}$ are easy to achieve.

There is other evidence that gas has been accelerated to quite high velocities in VRO 42.05.01. The Westerbork observations by Braun & Strom (1986a) show small H$\text{I}$ features in the wing region at velocities near $+20$ km s$^{-1}$. This differs by more than 50 km s$^{-1}$ from the systemic velocity of the SNR (see Section 3.3). Large velocities are also seen optically; Lozinskaya (1979) has measured the velocities of H$\alpha$ filaments in VRO 42.05.01 and obtained values in the range $+140$ to $-140$ km s$^{-1}$.

Because of these predictions, accelerated H$\text{I}$ has been searched for in many SNRs, but the confusion problem which plagues all galactic H$\text{I}$ studies has limited the convincing detections to a small number of objects. Braun & Strom (1986b) show an example of an H$\text{I}$ feature associated with the SNR IC443. This feature is of a comparable physical size to Feature K, and shows similar evidence of ablated material at velocity offsets up to 80 km s$^{-1}$. Landecker et al. (1980) observed small (up to 20 $M_\odot$) accelerated H$\text{I}$ cloudlets in the SNR G78.2+2.1 with velocity offsets of 40 and 110 km s$^{-1}$. Dubner, Colomb & Giacani (1986) have observed high-velocity H$\text{I}$ clouds coincident with G296.6+10.0.

4.4 COMPARISON OF H$\text{I}$ RESULTS WITH HIGHER RESOLUTION OBSERVATIONS

In this section we compare our H$\text{I}$ data with the maps by Braun & Strom (1986a) made with the Westerbork Synthesis Radio Telescope (WSRT). Their results are presented with an angular resolution of 1 x 1.5 arcmin$^2$ and a velocity resolution of 4 km s$^{-1}$. Our data, as presented in Figs 3–6, have 4 arcmin angular resolution and 5 or 2 km s$^{-1}$ velocity resolution. At first glance there is not a strong resemblance between the DRAO and WSRT maps, and this demands an explanation.

In comparing the two sets of maps, three factors must be borne in mind. The WSRT, because of its larger antenna elements, has higher sensitivity than the DRAO Synthesis Telescope. However, the larger WSRT antennas prevent the measurement of interferometer baselines shorter than 36 m. This is nearly three times the 13-m minimum baseline which the DRAO Synthesis Telescope can measure, and, furthermore, the DRAO data have been supplemented with single-antenna data, so that all baselines down to zero are represented in our maps. Braun & Strom state that their data are of ‘limited interpretive value’ when H$\text{I}$ emission fills their field of view (30 arcmin); under these circumstances bright emission features produce nearby negative depressions which can obscure weaker emission features or masquerade as absorption. Finally, the data of Braun & Strom have not been corrected for the primary response of the WSRT antennas. This tends to make large features appear concentrated towards the centre of the map when in reality they may extend beyond the map.

To explore the effect of missing baselines, we took selected maps from our data set and applied spatial filtering to remove all data corresponding to baselines of 0–36 m. We will discuss three specific examples. At 20 km s$^{-1}$, there was already a definite resemblance between the DRAO and WSRT maps; filtering the DRAO data improved the resemblance but removed 90 per cent of the power from the DRAO map. At $-44$ km s$^{-1}$ our maps show H$\text{I}$ Feature K (see previous section) of extent $\sim 15$ arcmin and peak brightness 12 K. Spatial
filtering removed most of the power from this quite small feature and any surviving emission was below the sensitivity limit of the DRAO observations. Similar remarks apply to the 20-arcmin H I feature seen in our data at +31.1 km s⁻¹ (Fig. 5).

The principal H I features which we associate with VRO 42.05.01 are: (a) the emission minimum, best seen at −28 and −30 km s⁻¹ which we identify with the old interstellar cavity, (b) a partial, expanding spherical shell at about −38 km s⁻¹, (c) the outline of the northern part of the wing at −34 to −40 km s⁻¹, (d) Feature K at −42 to −52 km s⁻¹. Each of these features can be recognized in the data of Braun & Strom, if the differences between the two telescopes are kept in mind.

Consider, as an example, Feature K. In the DRAO data we see evidence between −44 and −54 km s⁻¹ which indicates that this cloud has been shock accelerated. In this velocity range the WSRT observations show low-level features which bear a strong resemblance to continuum features of the SNR, namely one H I filament lying along the bright western edge of the wing, and another lying parallel to the linear continuum filament which crosses the centre of the remnant. Where the DRAO telescope shows a cloud of H I, the WSRT is sensitive only to the steep gradients at its peripheries. The high sensitivity of the WSRT can show these steep gradients. The fact that steep gradients exist at the edges of Feature K, and that they resemble the continuum structure, is further evidence that Feature K has been struck by the SNR shock. However, from the WSRT data alone it is not possible to derive a reliable estimate of the mass of gas in any of the H I features; unless the H I features are very small the effect of the missing baselines is to 'differentiate' the data. Nevertheless, the sensitive WSRT observations are of considerable value in revealing the morphological resemblances which the H I features bear to the continuum structure.

Similar remarks apply to other H I features. The DRAO observations show the northern end of the wing outlined in H I between −32 and −40 km s⁻¹. Again the WSRT sees H I features in this velocity range lying along the edges of the wing. H I features between −35 and −60 km s⁻¹ in the WSRT data are associated with the brightest continuum features of the wing of the SNR, in particular the bright western edge, the linear features, and the complex knots where the wing and the shell intersect. Our data show low-level features at many of these positions.

The WSRT observations also show emission at positive velocities (+10 to +35 km s⁻¹) which might be associated with the SNR. We can just detect these features on our maps as very weak protrusions on very large H I features, but from our data alone we definitely would not recognize them as having any association with VRO 42.05.01. At +19 km s⁻¹ Braun & Strom have detected H I features which seem to outline the wing. These may be associated with the interstellar cavity. The H I feature which we have detected at +31.1 km s⁻¹ (Fig. 5) has no counterpart in the Westerbork observations. It apparently has no small-scale H I structure, which may imply that it is not associated with the SNR.

We conclude that the WSRT and DRAO observations are complementary. Both have shown the presence of shocked H I within VRO 42.05.01. The high sensitivity of the WSRT observations has revealed small amounts of gas in filaments strongly resembling the continuum appearance of the SNR. The DRAO observations, with their superior sensitivity to broad structure, have revealed larger H I features such as the expanding shell at −38 km s⁻¹ and the shocked and ablated cloud at −43 to −52 km s⁻¹.

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