Modelling the bar in the centre of the starburst galaxy M82

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ABSTRACT
We present VLA A-array 21-cm atomic hydrogen (H\textsc{i}) absorption observed against the central region of the starburst galaxy M82 with an angular resolution of ~1.3 arcsec (=20 pc). These observations, together with MERLIN H\textsc{i} absorption measurements, are compared with the molecular (CO) and ionized ([Ne\textsc{ii}]) gas distributions and are used to constrain the dynamics and structure of the ionized, neutral and molecular gas in this starburst.

A position–velocity diagram of the H\textsc{i} distribution reveals an unusual ‘hole’ feature which, when previously observed in CO, has been interpreted as an expanding superbubble contained within a ring of gas in solid body rotation. However, we interpret this feature as a signature of a nearly edge-on barred galaxy. In addition, we note that the CO, H\textsc{i} and [Ne\textsc{ii}] position–velocity diagrams reveal two main velocity gradients, and we interpret these as gas moving on \(x_1\)- and \(x_2\)-orbits within a bar potential. We find the best fit to the data to be produced using a bar potential with a flat rotation curve velocity \(v_\circ = 140 \text{ km s}^{-1}\) and a total length of 1 kpc, a non-axisymmetry parameter \(q = 0.9\), an angular velocity of the bar \(\Omega_b = 217 \text{ km s}^{-1} \text{ arcsec}^{-1}\), a core radius \(R_c = 25 \text{ pc}\), an inclination angle \(i = 80^\circ\) and a projected angle between the bar and the major axis of the galaxy \(\phi' = 4^\circ\). We also discuss the orientation of the disc and bar in M82.

Key words: galaxies: individual: M82 – galaxies: kinematics and dynamics – galaxies: starburst.

1 INTRODUCTION
M82 is probably the best studied of the nearby starbursts and, as such, is a unique laboratory in which we can study the phenomenon of intense star formation. Owing to dust obscuration, the central region of this prototype starburst is best observed at infrared, millimetre and centimetre wavelengths. M82 has a high infrared luminosity which results from radiation from warm dust heated by hot young stars produced in the starburst (Rieke et al. 1980). In the radio, a large number of supernova remnants (SNRs) have been identified (e.g. Muxlow et al. 1994) and used as a probe of the star formation (Wills et al. 1997, 1998).

The molecular gas in the centre of M82 has been observed via numerous millimetre lines, including CO (e.g. Shen & Lo 1995; Neininger et al. 1998) and HCN (e.g. Brouillet & Schilke 1993). Interferometric observations allow angular resolutions of up to several arcseconds to be achieved which have revealed that a large fraction of the molecular gas is patchy and concentrated into dense clouds. Neutral hydrogen emission studies of M82 have been limited by instrumental sensitivity to angular resolutions poorer than 5 arcsec. However, by using neutral hydrogen absorption it is possible to observe neutral gas on scales limited only by the angular resolution of the instrument. In 1998, we reported pioneering MERLIN observations of this type against 33 SNRs in M82 (Wills et al. 1998). As a result we were able to probe the neutral hydrogen (H\textsc{i}) distribution on parsec scales (i.e. the size of individual SNRs). In this paper, we describe VLA A-array H\textsc{i} observations which, with the lower angular resolution and increased sensitivity to extended emission, allow the H\textsc{i} absorption against the more extended emission also to be studied.

The study of neutral hydrogen and molecular gas within M82 is important if we are to constrain a model of the mechanism whereby the activity can be induced. One hypothesis suggests that the interaction is induced directly as gas from one galaxy is removed and ‘dumped’ into another. Yun, Ho & Lo (1994) showed that a stream of H\textsc{i} links all three galaxies in the M81 group, and suggested that the M82 disc was probably originally quite substantial before the tidal disruption by M81. An alternative mechanism is that the interaction induces non-circular motions in the central regions which may lead to the formation of a bar (e.g. Noguchi 1988). The families of orbits that can exist within a barred potential may provide the dynamical transport necessary
for the fuelling of the starburst. Orientated along the bar axis are the $x_1$ family of orbits (Contopoulos & Mertzanides 1977) which give the bar its overall shape. At some energy the $x_1$-orbits can become self-intersecting (Binney & Tremaine 1987), and at this intersection the gas shocks, loses energy and falls inwards. The $x_2$-orbits are located closer to the nucleus, within the $x_1$-orbits, and are orientated perpendicular to the bar. These orbits provide a stable location for the infalling gas and help to transport the gas inwards.

A number of authors have discussed the possible existence of a stellar bar in M82. Lo et al. (1987) observed an asymmetric structure in the channel maps of their CO(1–0) observations and

Figure 1. Contour maps of every second channel of the continuum-subtracted spectral line cube throughout the velocity region containing the absorption. The maps show the depth of absorption as positive contours and have contour levels of $(-1, 1, 2, 4, 6, 8, 10, 11, 12, 14, 15, 16, 17, 18, 19, 20) \times 1.5$ mJy beam$^{-1}$. The central LSR velocity is given above each map. The final map shows a continuum image with contour levels of $(-1, 1, 2, 4, 8, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64, 68, 72, 76, 80, 84, 88) \times 1$ mJy beam$^{-1}$.
suggested a bar as a possible explanation. On the basis of their 2.2-μm observations, Telesco et al. (1991) proposed a bar of \(\sim 1\) kpc in projected length and inclined at \(\sim 22^\circ\) to the plane of the sky, with the eastern end being the most distant. Achtermann & Lacy (1995) investigated whether their [Ne\text{II}] line observations could be explained by \(x_1\) and \(x_2\) orbital families of a nuclear bar. In this paper, we provide the most compelling evidence to date that M82 does indeed contain a bar at its centre, and a model is developed. The distance of M82 is taken to be 3.2 Mpc (Burbidge, Burbidge & Rubin 1964).

2 OBSERVATIONS AND IMAGE PROCESSING

Observations of M82 were carried out on 1996 November 27 using the VLA in A-array configuration. The total used bandwidth was 3.125 MHz which was divided into 64 channels giving a
velocity resolution of 10.3 km s$^{-1}$. All velocities in this paper are quoted relative to the local standard of rest (LSR) (radio convention).

M82 was observed at a frequency corresponding to an LSR velocity of 225 km s$^{-1}$ for a total of 11 h. The phase and gain were calibrated with observations of 0859 + 681 every 30 min, and the absolute flux density scale was determined by observation of 3C 286. The bandpass calibration was obtained from observations of 3C 84. The resulting phase and gain corrections were applied to the spectral line data using aips, and the data were then Fourier transformed using uniform weighting to produce a 1024 $\times$ 1024 $\times$ 64 spectral line data cube.

3 RESULTS

A continuum image was obtained by averaging 18 channels free of line absorption (channels 2 to 15 and 55 to 59) in the uniformly weighted cube. In order to remove the sidelobe structure from the image, it was deconvolved using the maximum entropy method (MEM). The resulting image has a restored beamsize of 1.4 $\times$ 1.2 arcsec$^2$ and is shown as the final image in Fig. 1.

The uncleaned continuum image was subtracted from the ‘dirty’ cube in order to produce a continuum-subtracted spectral line cube. Each channel in this cube was deconvolved using the clean algorithm (Högbom 1974) and was convolved with a beamsize equal to that of the continuum image. In Fig. 1 we also show contour maps of every second channel of the continuum-subtracted spectral line cube that shows absorption.

Fig. 2 shows the moment 0 map produced from the continuum-subtracted cube, which illustrates the integrated absorption over the M82 continuum. In this case, the amount of absorption is biased by the strength of the continuum emission. Fig. 3 shows the velocities of absorption (moment 1) from the continuum-subtracted cube which indicate, in good agreement with previous results, that the position of maximum absorption shifts from west to east with increasing velocity.

Figure 2. The integrated absorption (moment 0) from the continuum-subtracted spectral line cube where the grey-scale range is from $-2.5$ to $0$ Jy beam$^{-1}$ km s$^{-1}$. Note that the absorption shown is dependent on the strength of the continuum emission.
The cleaned continuum was added back to the continuum-subtracted cube in order to produce an optical depth cube. This involved using the equation

$$\tau = -\ln(1 - T_L/T_C),$$

where $T_L$ is the line intensity, $T_C$ is the continuum intensity and $\tau$ is the optical depth, and we have assumed that the excitation temperature, $T_{\text{ex}}$, is very much smaller than $T_C$. Fig. 4 shows the moment 0 map from the optical depth cube. In order to produce this image, the optical depth cube has been generated from the continuum-subtracted cube in order to produce an optical depth cube. This involved using the equation
continuum image clipped at a level of 5 mJy. The 5-mJy level is illustrated as a dotted line in the plot. In contrast to Fig. 2, this moment 0 image is not biased by the strength of the continuum, although as a result of the clipping we can only detect absorption against the gas within the 5-mJy contour level. From this image we observe two concentrations of high optical depth on either side with a lower optical depth region in between. We also note that the eastern side shows the highest optical depth, and in between this eastern region and the centre we observe two ‘lanes’ of higher optical depth to the north and south with a much weaker region in between. To a lesser extent, two similar ‘lanes’ can also be seen to the west.

In Fig. 5 we show spectra obtained by integrating over the brightest four pixels (corresponding to 0.7×0.7 arcsec$^2$) of some of the SNRs that show H$_1$ absorption. Owing to the relatively poor angular resolution of these data compared with the MERLIN H$_1$ absorption data (see Wills et al. 1998), we only show a few examples of absorption spectra in cases where the SNR are clearly separated from other nearby remnants. Since the velocity resolution of these data is increased by a factor of ~2.5 with respect to the MERLIN H$_1$ data, it is interesting to compare the spectra of these remnants with the original spectra presented in Wills et al. (1998). In particular, we deduce the line velocities of the spectra presented here by fitting Gaussians to the absorption

\[ \text{Figure 5.} \text{ The spectra of a small sample of SNRs that show H}_1\text{ absorption in the VLA A-array data and are clearly separated from other remnants. The units of velocity are km s}^{-1}\text{.} \]
lines using the AIPS task SLFIT. These are compared with our previous results and presented in Table 1. As can be seen from this table, the higher velocity resolution VLA data indicate the presence of a number of additional absorption lines which were not previously recorded. Of the lines previously identified, we see good agreement in a number of cases regarding their precise velocity. In other cases we observe no direct agreement, and instead suggest that the line velocity previously recorded can be understood as an average of the velocities of the multiple lines now detected. In Wills et al. (1998) we argued that the double absorption spectra detected in a number of cases provided evidence of the complex gas motions in the central region. In this paper, these detected spectra greatly strengthen our argument, and in the following sections we suggest a model to explain these complex motions.

In order to reproduce position–velocity (p–v) diagrams of the VLA H\textsc{i} absorption data, it is necessary to rotate the H\textsc{i} distribution such that the major axis of the galaxy appears along the horizontal axis. The optimum angle for this procedure was found to be 17°. From this rotated image, the emission along the minor axis can then be effectively averaged together in predetermined regions to show how the velocity of the gas varies with position along the major axis in that region. Throughout this paper we take the centre of M82 to be at the position 9°51′43.4″, +69°55′00″ (1950) (Achtermann & Lacy 1995), and refer to this as 0 arcsec along the major axis and 0 arcsec along the minor axis. We present p–v diagrams of the H\textsc{i} optical depth cube for the minor axis regions −4.5 to −1 arcsec and −1 to 2.5 and 2.5 to 6 arcsec.

In Fig. 6 we show the locations of these minor axis regions with respect to the M82 continuum. Using 12\text{CO}(1−0) emission data kindly provided by Shen & Lo (see Shen & Lo 1995) and [Ne\textsc{ii}] emission-line data kindly provided by Achtermann & Lacy (see Achtermann & Lacy 1995), we have also been able to produce similar p–v diagrams for the molecular and ionized gas. The p–v diagrams for the H\textsc{i} optical depth cube, the CO and the [Ne\textsc{ii}] can be seen in Fig. 7. These p–v diagrams indicate that the rotation of gas in M82 is far more complex than just solid body rotation. The most striking feature is a ‘hole’ seen in a number of the plots on the western side.

In the lowest minor axis range (−4.5 to −1 arcsec) of the H\textsc{i} we observe a ‘hole’ structure in the p–v diagram on the western side. In the central minor axis range (−1 to 2.5 arcsec) of the H\textsc{i} we find that the eastern side of this ‘hole’ has become weaker although still detectable. By the highest minor axis range (2.5 to 6 arcsec) this feature is no longer visible. In the minor axis range −1 to 2.5 arcsec we note an additional weak component with a very steep gradient approximately 4 arcsec east of the centre with positive velocities. This lies next to a further steeper gradient component approximately 15 arcsec east of the centre, again with positive velocities. Together these two components bear similarity to the ‘hole’ seen on the western side. A hint of these two features can also be seen in the H\textsc{i} minor axis range −4.5 to −1 arcsec. We also observe an additional feature on the western side of the H\textsc{i} p–v diagrams with approximately zero velocity and a relatively flat gradient. This is clearly seen in the central minor axis range and weakly seen in the lowest minor axis range. By the highest minor axis range it is the most dominant, if not the only, feature on the western side. There does not appear to be any eastern equivalent to this component in any of the H\textsc{i} p–v diagrams.

In the CO we again observe the striking ‘hole’ feature on the western side for the minor axis ranges −4.5 to −1 and −1 to 2.5 arcsec. The eastern side of this feature can no longer be detected by the minor axis range 2.5 to 6 arcsec. For the minor axis ranges −1 to 2.5 and 2.5 to 6 arcsec in the CO we observe a relatively weak component with a steep gradient located at approximately 0 arcsec and with positive velocities. This appears again to form the western side of a far less striking ‘hole’ feature, where the eastern half can be seen most clearly in the range −1 to 2.5 arcsec with a steep gradient and at a position of approximately 10 arcsec east of the centre. This possible ‘hole’ feature appears to be related to that seen in the H\textsc{i} but is displaced approximately 4–5 arcsec to the west. There appears to be no sign in the CO of a flat gradient component as seen in the H\textsc{i}.

The ionized [Ne\textsc{ii}] gas plots, in all three minor axis regions, show a similar ‘hole’ feature on the western side. For the minor axis range 2.5 to 6 arcsec in [Ne\textsc{ii}] we observe a similar ‘hole’ feature on the eastern side, consisting of two well-separated components. The western component of this feature appears to extend with a steep velocity component to high positive velocities, which can be identified in all of the [Ne\textsc{ii}] minor axis regions. The eastern component of this ‘eastern’ hole is only really clearly seen in the range 2.5 to 6 arcsec. This ‘hole’ feature appears to be related to the similar features seen in both CO and H\textsc{i} and is located roughly mid-way between the two. In the ionized gas plots...
Figure 7. The p–v diagrams for the CO, H I and ionized [Ne II] gas in M82. Moving from left to right in each row of diagrams we see the minor axis ranges -4.5 to -1, -1 to 2.5 and 2.5 to 6 arcsec. The top row of diagrams show the CO distribution using $^{12}$CO(1–0) emission data, kindly provided by Shen & Lo (see Shen & Lo 1995). Moving from left to right along this row the grey-scale and contour levels in mJy beam$^{-1}$ are 0.3 to 1.2 and 0.3, 0.6, 0.9, 1.2; 0.2 to 1.5 and 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6; 0.25 to 1.4 and 0.25, 0.5, 0.75, 1.0, 1.25, 1.5. The next row of diagrams show the VLA H I absorption. The dashed lines in this row represent the region outside which blanking to a level of 5 mJy beam$^{-1}$ was necessary in order to produce the optical depth cube. Moving from left to right along this row the grey-scale and contour levels in optical depth units are 0.05 to 0.8 and 0.05, 0.15, 0.3, 0.45, 0.6, 0.75; 0.05 to 1.1 and 0.05, 0.15, 0.3, 0.45, 0.6, 0.75, 1.0; 0.08 to 1.0 and 0.08, 0.24, 0.48, 0.72, 0.96. The final row of diagrams show the ionized gas distribution using [Ne II] emission-line data, kindly provided by Achtermann & Lacy (see Achtermann & Lacy 1995). Moving from left to right along this row the grey-scale and contour levels in percentages of the peak are 5 to 100 and 10 to 100; 3 to 100 and 5 to 100; 8 to 100 and 10 to 100. In each case the lowest contour levels have been placed at the 3σ level and the velocity 0 km s$^{-1}$ represents the systemic velocity of 225 km s$^{-1}$. The centre of M82 is taken to be at the position $^{9}51^{m}43^{s}4$, +69° 55′00″ (Achtermann & Lacy 1995).
there appears to be no feature comparable to the flat gradient feature identified in the \textit{H}\textsubscript{i}.

We observe that most of the ionized gas appears to lie along a steep gradient of \(\sim 20 \text{ km s}^{-1} \text{ arcsec}^{-1}\), and most of the neutral and molecular gas has a gradient of \(\sim 6.5 \text{ km s}^{-1} \text{ arcsec}^{-1}\). However, there is a second, much weaker, component of the ionized gas which appears to lie along a flatter gradient. Interestingly, this weaker gradient is almost identical to the gradient fitting most of the \textit{H}\textsubscript{i} and CO. Moreover, the steeper gradient fitting most of the ionized gas is equal to the gradient of the steeper component seen as the eastern side of the western ‘hole’ and the steep component seen on the eastern side. This agreement seems far too striking to be merely a coincidence, and we discuss this observation in a later section.

4 DISCUSSION AND MODELLING

The \textit{H}\textsubscript{i} and CO \(p-v\) diagrams (Fig. 7) show the dynamics of the neutral and molecular gas in the central kiloparsec of M82 to be dominated by an approximately linear velocity gradient, consistent, to first order, with solid body rotation. However a cursory examination of these plots, together with the \textit{H}\textsubscript{i} absorption spectra presented both here and in Wills et al. (1998), demonstrates that significant non-circular motions are present. The ionized \([\text{Ne}\text{ii}]\) gas has a steeper gradient and smaller linear extent than the neutral gas, and has been modelled as a rotating disc within a bar structure by Achtermann & Lacy (1995). In this section we consider possible models to account for the non-circular motions in neutral, molecular and ionized gas.

4.1 An expanding superbubble?

The most prominent non-circular perturbation is present between 0 and 15 arcsec west from the centre of rotation (Fig. 7) and shows deviations of the order of 100 km s\(^{-1}\). This feature is present in CO, \textit{H}\textsubscript{i} and \([\text{Ne}\text{ii}]\) and shows significant changes along the minor axis. Only in the \([\text{Ne}\text{ii}]\) does it appear to present across all three minor axis ranges \((-4.5 \text{ to } 6 \text{ arcsec})\). In CO it is present from \(-4.5 \text{ to } 2.5 \text{ arcsec}\), whereas in \textit{H}\textsubscript{i} absorption it appears to be only strongly present from \(-4.5 \text{ to } -1 \text{ arcsec}\). Weiß et al. (1999) have attributed this feature to an expanding superbubble centred on the bright SNR 41.95 + 57.5 and associated with the giant \textit{H}\textsubscript{i} region seen in absorption by Wills et al. (1997) at 408 MHz. Wills et al. (1999) have compared the 408-MHz absorption with the \([\text{Ne}\text{ii}]\) emission of Achtermann & Lacy (1995) and deduced that the \textit{H}\textsubscript{i} region most likely has a shell-type structure. If the feature seen in the CO, \textit{H}\textsubscript{i} and \([\text{Ne}\text{ii}]\) \(p-v\) plots were associated with this shell then the observed expansion velocity of \(\sim 100 \text{ km s}^{-1}\) would clearly exceed the typical expansion velocities of normal \textit{H}\textsubscript{i} regions and must be due to some other effect such as a wind-driven shell. The \textit{H}\textsubscript{i} mass associated with such a shell can be estimated from Fig. 7. If we assume an optical depth of \(-0.2\) (i.e. \(N_{\text{H}} = 4 \times 10^{21} \text{ cm}^{-2}\)), a spin temperature of 100 K and that the feature has an extent of \(1.5 \times 3.5 \text{ arcsec}^2\), then this implies a mass of \(\sim 1.5 \times 10^{5}\) \(M_{\odot}\). Hence the energy required to accelerate the absorbing \textit{H}\textsubscript{i} is \(1.5 \times 10^{50}\) erg, although this is a lower limit since the \textit{H}\textsubscript{i} is only seen in absorption. If we assume that all the ionized gas estimated from Wills et al.’s (1997) absorption measurements is expanding at 100 km s\(^{-1}\), this has a kinetic energy of \(\sim 10^{52}\) erg. However, before pursuing this model further it is important to consider whether the feature really is an expanding shell.

There is no question that this feature is present in the data; the question is whether it really does correspond to an expanding superbubble. Our MERLIN \textit{H}\textsubscript{i} absorption measurements (Wills et al. 1998) show that 41.95 + 57.5 has at least two distinct velocity features at 87 and 200 km s\(^{-1}\). As Weiß et al. (1999) explained, although the 87 km s\(^{-1}\) component could be associated with the near side of an expanding shell, the 200 km s\(^{-1}\) feature cannot correspond to the far side unless the whole shell is in front of 41.95 + 57.5. This is not then consistent with a model of an expanding bubble associated with the bright remnant, and instead the location of the bright remnant at the centre of the proposed superbubble (in the sky plane) would have to be purely coincidental which seems somewhat contrived. Although Weiß et al. (1999) suggested that the poor velocity resolution (26 km s\(^{-1}\)) of the Wills et al. (1998) data could be used to resolve this problem, we feel that the double structure of the 41.95 + 57.5 spectrum was clearly demonstrated to be present since the two components were shown to be separated by an amount (113 km s\(^{-1}\)) much larger than the velocity resolution. In any case, our present data, observed with 10.3 km s\(^{-1}\) resolution (Fig. 5), unambiguously confirm this result.

In addition, we also observe a similar ‘hole’ feature on the eastern side which, although it is far less striking, appears to mirror the ‘hole’ on the western side. In the \textit{H}\textsubscript{i}, this feature is seen between 5 and 15 arcsec east of the rotation centre with velocities ranging from 25 to 130 km s\(^{-1}\). This is best seen in \textit{H}\textsubscript{i} absorption in the \(-1 \text{ to } 2.5 \text{ arcsec}^2\) plot and in ionized gas in the range 2.5 to 6 arcsec, although it is also weakly visible in other plots. The MERLIN \textit{H}\textsubscript{i} absorption measurements (Wills et al. 1998) against supernova remnants in this area show line splittings of \(\sim 90 \text{ km s}^{-1}\) (e.g. the SNR 45.48 + 64.8). Although this might be interpreted as another superbubble, we suggest that a more plausible explanation for both features is that they are a natural consequence of gas motions in a barred potential. Kuijken & Merrifield (1995) have emphasized the importance of ‘hole’ and ‘figure of eight’ type structures in \(p-v\) plots as a diagnostic of edge-on barred spirals. Given the large amount of other evidence that M82 has a central bar (e.g. Telesco et al. 1991; Achtermann & Lacy 1995), it seems unnecessary to invoke a superbubble explanation for these features.

From Fig. 7 it seems clear that the eastern side of the feature originally interpreted as the ‘superbubble’ is closely dynamically associated with the steep gradient in the \([\text{Ne}\text{ii}]\) which Achtermann & Lacy (1995) have identified as part of a rotating ionized ring. From Fig. 7 we observe that, particularly in the two southern \(p-v\) plots, the velocity gradient of most of the ionized \([\text{Ne}\text{ii}]\) gas is much steeper \((\sim 20 \text{ km s}^{-1} \text{ arcsec}^{-1})\) than the typical velocity gradients of the neutral and molecular \((\textit{H}\textsubscript{i}+\text{CO})\) gas \((\sim 6.5 \text{ km s}^{-1} \text{ arcsec}^{-1})\). Furthermore, the linear extent of the ionized gas \((30 \text{ arcsec} = 450 \text{ pc})\) is significantly less than that of the \textit{H}\textsubscript{i} or the CO. Hence, to first order, the ionized and neutral components appear to be dynamically separate, and therefore it seems reasonable, if we evoke a bar model, to associate the bulk of ionized gas with the inner \(x_2\)-orbits of the bar and the neutral gas with the outer \(x_2\)-orbits. Thus the eastern part of the feature originally interpreted as a superbubble appears to be due to a small fraction of the neutral gas associated with \(x_2\)-orbits. The western side of this feature could be due to transition of gas in \(x_1\)-orbits to \(x_2\)-orbits via a shock. We therefore conclude that the ‘hole’ features are actually the signature of an almost edge-on bar. Unlike in theoretical models (e.g. Bureau & Athanassoula 1999), the pattern does not appear to be completely symmetric since the
‘hole’ feature on the western side is far more striking. However, this is not dissimilar to observations of other barred systems where the shocks in the bar can clearly be seen to be asymmetric (e.g. NGC 4151; Mundell et al. 1999).

4.2 A bar in M82?

Cold gas, unlike stars, is a highly dissipative system. Neutral gas clouds will tend to collide and in the process dissipate energy. Hence, in a galaxy, cold gas will tend to settle on non-self-intersecting closed orbits. In a bar potential the neutral gas will therefore be in the plane of the galaxy moving along closed orbits. Simulations in the literature have shown that a bar usually has two intersecting closed orbits. In a bar potential the neutral gas clouds will tend to collide and in the process dissipate energy.

4.2 A bar in M82?

NGC 4151: Mundell et al. 1999). The x2-orbits exist when there is an inner Lindblad resonance (ILR) ring in the galaxy which occurs when there are radii at which the relation \( \Omega(R) - \Omega_b = k/2 \) is satisfied. Here \( \Omega(R) \) is the angular speed of the particle, \( \Omega_b \) is the angular speed of the bar and \( k \) is the epicyclic frequency. As the gas flows along the x1-orbits, the crowding of clouds at the ends of the bar results in enhanced star formation at these points. As a result the clouds lose angular momentum and sink into the nucleus of the galaxy (Jenkins & Binney 1994). Simulations of bars have shown that the x2-orbits develop when gas is funnelled into the centre of the galaxy by the gravitational torques exerted by the bar (e.g. Friedli & Benz 1993). Clouds move in a dynamical time-scale from the x1- to the inner x2-orbits mainly as a result of losing angular momentum to the stellar bar after piling up behind the shock that forms along two of the nearly straight line segments of the cusped orbit (Athanassoula 1992). This results in large amounts of star formation and gas accumulation in the centre of the galaxy. Hence many barred galaxies, especially the gas-rich bars, show enhanced star formation at the ends of the bar and across the bar at the intersection of the x1- and x2-orbits (Kenney et al. 1992). The central build-up of gas can often result in a nuclear starburst in a barred galaxy, such as that seen in NGC 253 (e.g. Anantharamaiah & Goss 1996).

M82 has a strong nuclear starburst region with a ring-like appearance. In this section we investigate a bar model for M82 and, in particular, model the gas and star-forming regions as lying on bar and anti-bar orbits. This approach of modelling gas in a bar potential was first used by Binney et al. (1991) in order to explain the distribution of gas in the centre of our own Galaxy. Following this, similar methods have been applied to other barred galaxies (e.g. NGC 253: Peng et al. 1996; M31: Stark & Binney 1994). For M82, we have used a simple logarithmic potential to model the bar based on a few parameters from the rotation curve of the galaxy. A more detailed model such as treating the bar as a prolate body (as used in Binney et al. 1991) is not attempted here as the density distribution in the bulge is not well known for M82. However, we hope to model the bar in more detail in a later paper when more data on the mass distribution are available. The potential is given by

\[
\Phi(x, y) = \frac{1}{2} v_b^2 \ln \left( x^2 + y^2 + R_c^2 \right) \tag{2}
\]

(Binney & Tremaine 1987), where \( v_b \) is the velocity in the flat portion of the rotation curve of the galaxy, \( q \) is the non-axisymmetry parameter and \( R_c \) is the core radius. To determine the closed orbits in the bar potential, we need to use the equation of motion in the rotating frame of the bar. This is given by

\[
r = - \nabla \Phi - 2(\Omega_b \times \mathbf{v}) - \Omega_b \times (\Omega_b \times r),
\]

where \( r \) is the position vector of a particle in the bar, \( \mathbf{v} \) is the velocity of a particle in the rotating frame of the bar and \( \Omega_b \) is the angular velocity of the bar.

The parameters defining the bar potential are \( v_b, \Omega_b, R_c \) and \( q \), of which \( v_b \) and \( \Omega_b \) can be determined, to first order, from the observed rotation curve of the galaxy (e.g. the M82 \(^{12}\)CO rotation curve of Neininger et al. 1998). By varying the parameters we find the best fit to the data to be with a value of \( v_b = 140 \text{ km s}^{-1} \) and \( q = 0.9 \). The semi-major axis of the bar was taken to be 500 pc so the deprojected bar length, \( l \), is 538 pc (Arnaboldi et al. 1995). The rotation speed of the bar is given by \( \Omega_b = v_b/R_{CR} \), where \( R_{CR} \) is the corotation radius in the bar and is 1.2 times the length of the bar, \( l \). So we obtain a value of \( \Omega_b = 217 \text{ km s}^{-1} \text{ kpc}^{-1} \) for the bar rotation speed in our model, where \( v_b = 140 \text{ km s}^{-1} \) and \( R_{CR} = 1.2l \). We varied \( R_c \) in order to choose a value that gave a large population of x1- and x2-orbits. For \( R_c > 25 \text{ pc} \) we could not obtain the x1- and x2-orbits and instead the bar structure appeared only for values of \( R_c \leq 25 \text{ pc} \). Hence the upper limit \( R_c = 25 \text{ pc} \) is used in the final model. It must, however, be noted that the value of \( R_c \) is not unique, since values lower than 25 pc will give similar results. These different values of \( R_c \leq 25 \text{ pc} \) do not produce significant changes in the model as long as \( R_c \gg 0 \). The x1-orbits that were found to be self-intersecting at the ends were not used in the final model, since gas will not settle on self-intersecting orbits where the cloud collision probability is high.

The x1- and x2-orbits and the corresponding particle velocities along the closed trajectories can be used to determine the theoretical p–v diagram for the galaxy. This model p–v diagram can then be compared with that observed. To construct the p–v diagram we need to project the orbits on to the plane of the sky. The projected length of the bar \( l_{obs} \) is related to the true bar length \( l \) by

\[
l_{obs} = l \sqrt{\cos^2 \phi + \sin^2 \phi \cos^2 i},
\]

where \( \phi \) is the angle between the bar and the major axis of the

![Figure 8. The p–v diagram of the closed orbits, x1 and x2, produced in a bar model with \( v_b = 140 \text{ km s}^{-1} \), \( q = 0.9 \), \( \Omega_b = 217 \text{ km s}^{-1} \text{ arcsec}^{-1} \), \( R_c = 25 \text{ pc} \), \( i = 80^\circ \) and \( \phi' = 4^\circ \). These parameters produce the best fit to the data presented in this paper.](https://academic.oup.com/mnras/article-abstract/316/1/33/1119784)
galaxy in the plane of the galaxy, and \( i \) is the angle of inclination of the galaxy (Arnaboldi et al. 1995). The projection of the angle \( f \) on to the plane of the sky is given by \( f' \), where
\[
\tan f' = \tan f \cos i.
\]  
In addition, we also need to determine the radial velocity associated with points along the closed orbits. The velocity components in the rotating frame are transformed to the inertial frame and the final expression for the radial velocity \( v_{\text{rad}} \) is given by
\[
v_{\text{rad}} = [(v_x - \Omega_{y}) \sin \phi + (v_y + \Omega_{z}) \cos \phi] \sin i.
\]  
Hence, for every point \( r(x, y) \) along the closed trajectories, there is a corresponding radial velocity \( v_{\text{rad}} \). This velocity and the position along the galaxy axis for the different \( x_1- \) and \( x_2- \)orbits can then be used to construct the model p–v diagram. The resulting diagram is shown in Fig. 8. The inclination angle and the projected angle of

\[\begin{align*}
\text{CO -4.5'' to -1''} & \quad \text{Velocity (km/s)} \\
\text{Major Axis (arcsec)} & \quad \text{Velocity (km/s)} \\
\text{HI -4.5'' to -1''} & \quad \text{Velocity (km/s)} \\
\text{Major Axis (arcsec)} & \quad \text{Velocity (km/s)} \\
\text{[NeII] -4.5'' to -1''} & \quad \text{Velocity (km/s)} \\
\text{Major Axis (arcsec)} & \quad \text{Velocity (km/s)} \\
\text{HI -1'' to 2.5''} & \quad \text{Velocity (km/s)} \\
\text{Major Axis (arcsec)} & \quad \text{Velocity (km/s)} \\
\text{[NeII] -1'' to 2.5''} & \quad \text{Velocity (km/s)} \\
\text{Major Axis (arcsec)} & \quad \text{Velocity (km/s)} \\
\text{HI 2.5'' to 6''} & \quad \text{Velocity (km/s)} \\
\text{Major Axis (arcsec)} & \quad \text{Velocity (km/s)} \\
\text{[NeII] 2.5'' to 6''} & \quad \text{Velocity (km/s)} \\
\text{Major Axis (arcsec)} & \quad \text{Velocity (km/s)}
\end{align*}\]
the bar with respect to the galaxy axis were both varied. We found that the best fit to the data was obtained using the values of $i = 80^\circ$ for the inclination angle and $\phi' = 4^\circ$ for the projected angle of the bar, in good agreement with values suggested by Telesco et al. (1991).

In Fig. 9 we present the $p-v$ diagrams of Fig. 7 on to which the bar model predictions have been superimposed. As can be seen, the $x_1$-orbits of the bar fit with good agreement along most of the neutral and molecular gas emission, whereas most of the ionized gas fits along the steeper $x_2$-orbits, as previously suggested. The steeper $x_2$-orbits also fit to the steep gradient features observed in the H\textsc{i} and CO 'hole' features. The flatter $x_1$-orbits are also able to explain the flatter gradient component seen in the ionized gas, particularly towards the higher minor axis regions. The western side of the feature originally interpreted as a superbubble shows a good fit to the cusped $x_1$-orbit. This orbit is responsible for transporting gas from the outer to the inner orbits. As previously noted, the 'hole' on the opposite side is far less striking, and we also observe that the fit to the cusped orbit on this side is far less impressive. In addition the fits show that the bar appears to be truncated on this side. As previously suggested, we interpret these observations as the bar in M82 being somewhat one-sided.

The flat gradient component seen only in the H\textsc{i} does not fit to the bar model, and instead we interpret this feature as resulting from H\textsc{i} absorption from the outer disc of M82, thus accounting for its low velocity, flat gradient and relatively small linewidth. In our own Galaxy the outer disc is seen much more strongly in H\textsc{i} than in molecular gas (e.g. Liszt 1992), and in M82 it seems that this disc component is not detected in CO at all. This H\textsc{i} disc component in M82 is only observed on the western side, presumably because on the eastern side it becomes confused with the rest of the absorption.

In addition to the bar model showing a good fit to the CO, H\textsc{i} and [Ne\textsc{ii}] data, it also shows a good fit to the absorption spectra against the SNRs. In Fig. 10 we show the bar model with the positions and velocities of the absorption against the SNRs superimposed. This uses the MERLIN H\textsc{i} absorption data presented in Wills et al. (1998). Such an impressive fit is not obtained with the model of a single expanding superbubble surrounded by gas moving in solid body rotation, since a number of the double absorption features detected are located away from the proposed site of the expanding superbubble. The plot suggests that absorption is taking place against both sides of the $x_1$- and $x_2$-orbits, which implies that the remnants are distributed around both sets of orbits with a significant number to the back. In Fig. 11 we show a similar plot for four of the SNRs using the VLA H\textsc{i} absorption data presented in this paper. Here we see a reasonable fit to the data, with the exception of a number of points in the west which seem to have velocities much closer to the systemic velocity than that predicted by the bar model. We note that these points are located along the flat velocity gradient component seen in the H\textsc{i} $p-v$ diagrams, which does not fit to the bar model. We interpret this as H\textsc{i} absorption against the SNR by the disc of M82. On the eastern side we observe one of the absorption points being somewhat lower than the bar model predicts. This is possibly also due to the disc component on the other side, although the result is not as clear as for the western side. Presumably this effect is not seen with the MERLIN H\textsc{i} absorption results because the disc component is resolved out by the high-resolution data.

This paper has shown that the ionized gas in M82 appears to be rotating more rapidly than the neutral and molecular gas, and in addition is more centrally confined. In terms of the bar model we interpret this as the $x_2$-orbits being dominated by ionized gas, whilst the $x_1$-orbits are dominated by the neutral and molecular material. As far as we understand it, this is the first barred galaxy to show such a dynamical and spatial distinction between ionized and non-ionized material. Figs 10 and 11 have demonstrated that

![Figure 10](https://example.com/figure10.png)  
**Figure 10.** The bar model with the positions and velocities of the absorption against the SNRs superimposed. This uses the MERLIN H\textsc{i} absorption data presented in Wills et al. (1998), and shows the velocity as a solid line which stretches the length of the error in the measurement.
the SNR distribution extends across the $x_1$- and $x_2$-orbits and does not appear to be centrally concentrated. From this SNR distribution we can conclude that the starburst 10$^7$ yr ago was localized around both the $x_1$- and $x_2$-orbits with an approximately equal distribution. In contrast, since the ionized gas distribution is mainly found along the $x_2$-orbits, this suggests that the current starburst is more centrally confined. We are perhaps, therefore, seeing evidence of the starburst moving inwards on a time-scale of $\sim$10$^7$ yr. This argument is also supported by Fig. 12, in which we show the [Ne$\text{II}$] distribution of Achtermann & Lacy (1995) and the positions of the individual SNRs detected at 5 GHz (from Wills et al. 1997). This figure shows how the SNRs appear to avoid the peaks of the ionized gas, which was interpreted by Achtermann & Lacy (1995) as the starburst moving inwards. In

Figure 11. The bar model with the positions and velocities of the absorption against the SNRs superimposed. This uses the VLA H$_1$ absorption data presented here, and shows the velocity as a solid line which stretches the length of the error in the measurement.

Figure 12. The ionized gas distribution of Achtermann & Lacy (1995) shown as a contour image, and the SNRs detected at 5 GHz (from Wills et al. 1997) shown as small squares. The contour levels are spaced linearly.
addition, Fig. 12 also shows how the SNR distribution appears to be spread over a larger spatial extent than that of the ionized gas. This is also suggested by Fig. 13 which shows the number of SNRs distributed in different bins across the major axis and how this compares with the ionized gas peaks along the major axis. The ionized gas peaks are shown by plotting the maximum [Ne II] contour level that crosses a line parallel to the minor axis at individual positions along the major axis. This diagram also suggests that the current starburst is confined to a smaller region along the major axis than the starburst 10⁷ yr ago.

The variation observed in the CO, H i and ionized gas p–v diagrams between the different minor axis ranges must occur as a consequence of the orientation of M82. Although the galaxy has been rotated (by 17°) such that the major axis is aligned along the horizontal, there must still be some variation left in the position of the orbits with respect to the minor axis. In Fig. 14 we have taken two three-dimensional ellipses with a circular cross-section and placed them at 90° to each other in order to represent simplistically the x₁- and x₂-orbits. We have then placed these orbits at an inclination angle of 80° with the x₁-orbit aligned at an angle of 22° to the plane of the sky, as suggested by Telesco et al. (1991). These two parameters result in the projected angle of the bar with respect to the galaxy axis being 4°, a parameter used in our model. Fig. 14 shows the view of these orbits as seen from the Earth if the major axis of M82 is horizontal. As suggested, there is indeed still some variation in the position of the orbits for the different minor axis regions. The most striking variation is caused by the orientation of the x₂-orbits. This orientation suggests that in the lowest minor axis regions we should observe the western side of the x₂-orbits, and in the highest minor axis regions the eastern side of the x₂-orbits should be more clearly visible. In fact this is in good agreement with our observations, since the western `hole' feature, part of which is attributed to the x₂-orbits, is most clearly seen in the lowest and central minor axis regions of the H i and the CO. By the highest minor axis range in the CO and the H i the x₂-orbits on the western side are no longer visible. In contrast, the x₂-orbits on the eastern side are not at all visible in the lowest minor axis region of the CO, but are visible by the highest minor axis region. In the ionized gas the x₂-orbits on the eastern side are quite clearly seen in the highest minor axis range, but are much more weakly visible in the lowest minor axis range. The variation of the x₁-orbits with minor axis is much more difficult to observe, since it is a smaller angle dependence. However, it is still possible to observe in the CO and the [Ne II] that the western side of the x₁-orbits becomes more visible towards the highest minor axis range. In the production of Fig. 14 we have used an angle of inclination of 80° such that the south is the more distant side, and an angle between the bar and the plane of the sky of 22° such that the eastern side is more distant. This is the orientation suggested by Telesco et al. (1991) which produces the observed angle of 4° between the bar and the major axis of the galaxy. The bar is observed to be at a smaller angle to the horizontal than the major axis of the galaxy. However, it is also possible to produce the same 4° angle between the bar and the major axis by using an inclination angle of 80° with the south as the more distant side, and an angle of 22° between the bar and the plane of the sky with the western side more distant. As far as Fig. 14 is concerned, the result would be identical. Telesco et al. (1991) chose the inclination with the south as the more distant side because of the observations that the southern half of the galaxy is more heavily reddened (Notni & Bronkalla 1983) and more polarized (Chesterman & Pallister 1980) than the northern half. This orientation then requires the eastern side of M82 to be the more distant if we are to obtain the 4° shift in the direction observed between the bar and the major axis of the galaxy. In Wills et al. (1997) we observed that there is an increase in ionized gas absorption towards the north of the galaxy. If we simplistically assume that the SNRs and more extended radio emission are distributed outside the ionized gas distribution then this result suggests that the northern side of the bar is the more distant side. In turn this also implies that the western side of the bar is more distant than the east. We note that these results therefore suggest the opposite orientation to that previously suggested for the outer part of the galaxy.

In Fig. 15 we present an ‘unsharp masked’ 5-GHz image of M82. The process by which this image was produced is described in detail in Wills et al. (1999), but basically it shows an SNR-subtracted smoothed 5-GHz VLA A + B-array image of the radio

![Figure 14. Two three-dimensional ellipses with a circular cross-section have been placed at 90° to each other in order to represent simplistically the x₁- and x₂-orbits. These orbits have been rotated to an inclination angle of 80° with the x₁-orbit aligned at an angle of 22° to the plane of the sky. This shows how the orbits would look to an observer on the Earth if M82 were rotated by 17° such that the galaxy axis appears horizontal in the plane of the sky. Although the galaxy axis is horizontal, the bar then lies at angle of 4° below the horizontal, ϕ = 4°.](https://academic.oup.com/mnras/article-abstract/316/1/33/1119784/3161131119784)
synchrotron emission. Once the complexity of the SNR distribution has been removed, we can study the remaining simple distribution of the synchrotron emission. The resulting image appears to show a small inner ring structure with two ‘arms’ extending from it. Comparing this image with the simplified Earth view of the \( x_1 \)- and \( x_2 \)-orbits rotated to a position angle of 17\(^\circ\) yields a striking result: we appear to be observing the bar structure of the radio synchrotron emission. The inner ring appears to be barred \( x_2 \)-orbits and the outer ‘arms’ appear to represent a nearly edge-on view of the \( x_1 \)-orbits.

5 CONCLUSIONS

In this paper we have presented VLA H\( \text{I} \) absorption data against the central region of the M82 continuum. We have produced position–velocity diagrams of these data for different minor axis regions of M82, and compared these with similar plots for the CO and ionized \([\text{Ne} \, \text{II}] \) gas. Our H\( \text{I} \) absorption data have revealed the presence of a striking ‘hole’ feature previously identified in the CO and interpreted as a large expanding superbubble centred on the brightest remnant, 41.95 + 57.5. In this paper we argue for an alternative explanation for this feature. We first show, from the H\( \text{I} \) absorption detected against this bright source, that this remnant cannot be dynamically centred inside this unusual feature. Instead, we note that a similar ‘hole’ feature, although much less striking, can also be seen on the opposite side of the \( p-v \) diagrams, and interpret the features as a signature of a nearly edge-on barred galaxy.

We observe that the H\( \text{I} \), CO and \([\text{Ne} \, \text{II}] \) \( p-v \) diagrams consist of two different velocity gradient components. The ionized gas appears to be dominated by a faster rotating component, whilst the neutral and molecular gas is dominated by a much slower component. We interpret these two components as gas moving on \( x_1 \)- and \( x_2 \)-orbits of a barred potential such that the inner \( x_2 \)-orbits are dominated by ionized gas and the outer \( x_1 \)-orbits are dominated by neutral and molecular gas. We investigated different parameters of the bar and found the best fit to the data using a bar potential with \( v_b = 140 \text{ km s}^{-1} \) and a total length of 1 kpc, \( q = 0.9 \), \( \Omega_b = 217 \text{ km s}^{-1} \text{arcsec}^{-1} \), \( R_b = 25 \text{ pc} \), \( i = 80^\circ \) and \( \phi' = 4^\circ \). The ‘hole’ feature, previously interpreted as the superbubble, appears to fit with good agreement to this model. The eastern side of this feature appears to be produced by gas moving along the \( x_2 \)-orbits and the western side appears to be gas moving along the cusped \( x_1 \)-orbit which is responsible for transporting gas inwards from \( x_1 \) to \( x_2 \). Our observation of this feature therefore represents direct evidence for the fuelling of the starburst towards the centre.

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