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21-cm observations of the interacting galaxies M81 and M82

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Summary. The Cambridge Half-Mile Telescope has been used to map the H I distribution and velocity field in the region surrounding the peculiar Irr II galaxy M82 with an angular resolution 2×2.1 arcmin. The maps reveal a clumpy H I bridge stretching between M81 and M82 which, at either end, merges into the galaxies with radial velocities appropriate to their optical recession velocities. Neutral hydrogen above the plane of M82 exhibits a radial velocity gradient in the sense that higher H I radial velocities are found in the north of the galaxy than in the south. The velocity gradient is in the same sense as that found optically in the filaments and may be gas which has been captured from M81 in a single hyperbolic tidal encounter $\sim 1.8 \times 10^8$ yr ago. Evidence for a diminution in the H I surface density along the north axis of M82 coincident with part of the Hα filamentary system suggests that there is dynamical coupling between filaments and gas. A possible model of the filaments is one in which they are composed of dusty plasma accelerated away from the galactic nucleus under radiation pressure forces transmitted via the dust grains, and have swept out cavities in the surrounding H I cloud. In order to account for the observed blueshifts of the filaments on the south of M82, these must have interacted with the gas in the outer parts of the galaxy.

1 Introduction

The distribution of neutral hydrogen in the vicinity of the small group M81, M82 and NGC 3077 is known to be unusual (e.g. Davies 1974). The dominant member is M81, a giant Sb galaxy (Plate 1) which has been mapped in H I by Rots & Shane (1974) and Gottesman & Weliachew (1975). Both of M81's companions are of the rare Irr II type. NGC 3077 has a peculiar H I tail pointing towards M81 (Cottrell 1976), which suggests a tidal origin in a close encounter $\sim 2 \times 10^8$ yr ago. H I studies of M82 (Volders & Högbom 1961; Roberts 1972) have hitherto been limited to angular resolutions $\gtrsim 10$ arcmin and it was felt that a survey with a higher angular resolution, i.e. 2 arcmin, would be of interest, particularly since there is evidence (Rots 1974) that M82 has interacted tidally with M81. M82 (NGC 3034)

(Plate 1) has an oblong shape suggestive of a disc galaxy seen nearly edge-on, but the chaotic system of dust-lanes, irregular luminous patches and filaments (Plate 2) indicates that it is a highly disturbed object. The filaments radiate both in Hα and the continuum, and exhibit a velocity field which was interpreted by Lynds & Sandage (1963) as evidence for explosive ejection of matter from the nucleus $\sim 10^6$ yr ago. The nucleus contains the complex radio source 3C 231 which has been mapped recently by Hargrave (1974) and Kronberg & Wilkinson (1975).

In Section 2 the observations and data reduction are described and in Section 3 the results are presented. The discussion in Section 4 centres on the dynamical state of the gas around M82 in relation both to a tidal interaction with M81 and to the origin and dynamics of the filaments.

2 The observations and data reduction

The Cambridge Half-Mile Telescope (Baldwin *et al.* 1971) was used during 1975 January–March and again during 1976 April–May to observe at a total of 48 interferometer spacings. The spacing increment was 6.1 m and the lowest spacing was 12.2 m (58λ), so angular structure on scales $\gtrsim 1^\circ$ is attenuated by the telescope response and no structure on scales larger than $3^\circ.8$ is recorded. The first grating response is 2° from the centre of M82. The FWHM of the synthesized beam was 2 x 2.1 arcmin which, at the distance assumed for M82 (3.25 Mpc), corresponds to an area on the sky of $1.9 \times 2.0\,\mathrm{kpc}^2$. A further series of maps from the observations at the 24 lowest spacings was made in order to study the emission of low surface brightness in the region containing the bridge (discussed in Section 3.1.2). These have a synthesized beam of FWHM 3.9 x 4.1 arcmin (≡3.7 x 3.9 kpc).

The telescope phase and sensitivity were calibrated at each spacing by observations of 3C 309.1, assumed to have a flux density of 7.9 Jy (Kellermann, Pauliny-Toth & Williams 1969). Hughes, Thompson & Colvin (1971) were unable to detect any H I absorption in the spectrum of 3C 309.1 in the radial velocity range −146 to 22 km/s and placed an upper limit of 0.04 on the optical depth, for which no correction has been made in this paper. The passband of the cross-correlation spectrometer was 4 MHz centred on a frequency 1419.5 MHz ($V_r \approx 200$ km/s), and the hydrogen-line spectra were sampled at intervals of 125 kHz (26.4 km/s), the FWHM of the response being 150 kHz.

A serious problem in producing synthesis maps of H I in M82 is the degree to which sidelobes from the continuum source can be subtracted. An observation at a single spacing synthesizes a ring-aperture which, on Fourier inversion, gives a $J_0(x)$ Bessel function response to a point source. The *deepest* sidelobes are therefore $\lesssim 0.4$ of the peak response. If there are daily errors in the calibration of the amplitude and phase of ΔA per cent and $\Delta\phi$ respectively, then the rms level of residual continuum sidelobes after subtraction on an n-spacing map is

$$\sigma_s \lesssim 0.4\, T_0\, n^{-1/2}\; [(\Delta A)^2 + (\sin \Delta\phi)^2]^{1/2}\,\mathrm{K},$$

where T_0 ($\propto n^2$) is the brightness temperature of the continuum source on the map. Tests on the day-to-day stability gave $\Delta A \approx 1$ per cent and $\Delta\phi \approx 1^\circ$, so σ_s could be calculated. In Table 1, σ_s is compared with the *measured* rms noise (σ_N) on the maps, and the expected noice (Baldwin *et al.* 1971) for a single-channel bandwidth of 150 kHz and a system noise temperature of 120 K. It can be seen that (i) the measured noise level far from sources is close to that predicted and (ii) the sidelobe contribution is small. On the final maps no H I emission can be observed inside the radii of the *full width* of the beam (2 and 4 arcmin respectively for the 48- and the 24-spacing maps). This is because: (i) H I is observed in

Table 1.

n	σ_N/K	σ_s/K	σ_T/K
24	0.6	0.15	0.4
48	1.25	0.25	1.05

absorption against the continuum source which occupies the central beam area, and (ii) the measured H I flux at the position of the central source depends on the subtracted flux density, which is subject to an error large by comparison with the H I flux density in adjacent beam areas.

On the 2-arcmin maps, H I emission was detected in a region $\lesssim 15$ arcmin from the nucleus of M82 on 12 single-channel maps. Remaining maps in the velocity ranges 554 to 369 and −26 to −158 km/s were averaged and subtracted from the single-channel maps to generate a set of continuum-free maps of H I emission and absorption. The negative 'absorption source' was between 10 and 15 per cent of the peak brightness temperature of the continuum (indicating optical depths of that order). The centroid of the absorption source showed a systematic displacement with radial velocity, in agreement with Weliachew's (1974) results. To remove the sidelobes due to this unresolved absorption source, the interferometer response to a point source was added to each of the single-channel maps so as to cancel the absorption source at the position of the absorption centroid.

Fourteen of the 4-arcmin maps (in the velocity range 362–21 km/s) showed H I emission both from around M82 and from the bridge. These maps were analysed in the same way as the 2-arcmin set, using continuum measurements in the same velocity range. The lower limit in the velocity integral of the integrated hydrogen maps of +21 km/s was chosen for two reasons: (i) there was no significant H I emission from the region containing M82 and the bridge on single-channel maps of lower radial velocity, and (ii) the maps will not be contaminated by local H I.

The integrated hydrogen maps (Plates 1 and 2; Figs 1 and 2) were made by (a) setting to zero all data on the 12 single-channel maps showing H I less than 1.5 σ_N, (b) addition of data, and (c) correction for the primary beam response. In addition, radial velocity maps (Figs 3 and 4) were made which represent for each grid point the mean of the two radial velocities at which the H I profile had dropped to half its peak value. The instrumental broadening of profiles is 31.7 km/s.

3 The distribution and velocity field of the H I

3.1 THE RESULTS AT A RESOLUTION OF 4 ARCMIN

3.1.1. The region around M82

Plate 1 and Fig. 1 reveal the bulk of H I close to M82 to lie in an extended region $\approx 18 \times 10$ arcmin, which is approximately aligned with the optical major axis (position angle 62.°5). With no correction for self-absorption, the H I mass is $(9.4 \pm 1) \times 10^8 M_\odot$, but $(10 \pm 1) \times 10^8 M_\odot$ after correction for an optical depth of 0.1 (Section 2). The radial velocity field (Fig. 3) reveals a net gradient aligned with the *minor* rather than the major axis of the galaxy, and therefore the gas is not in stable circular orbits in the disc. The apparent value of this gradient, ≈ 23 km/(s kpc), is a lower limit because of beam-smoothing effects.

3.1.2 The bridge

The widely dispersed nature of the bridge makes it difficult to distinguish between bridge and galaxy. However, the total mass of optically thin H I on Fig. 1, exterior to the ellipses

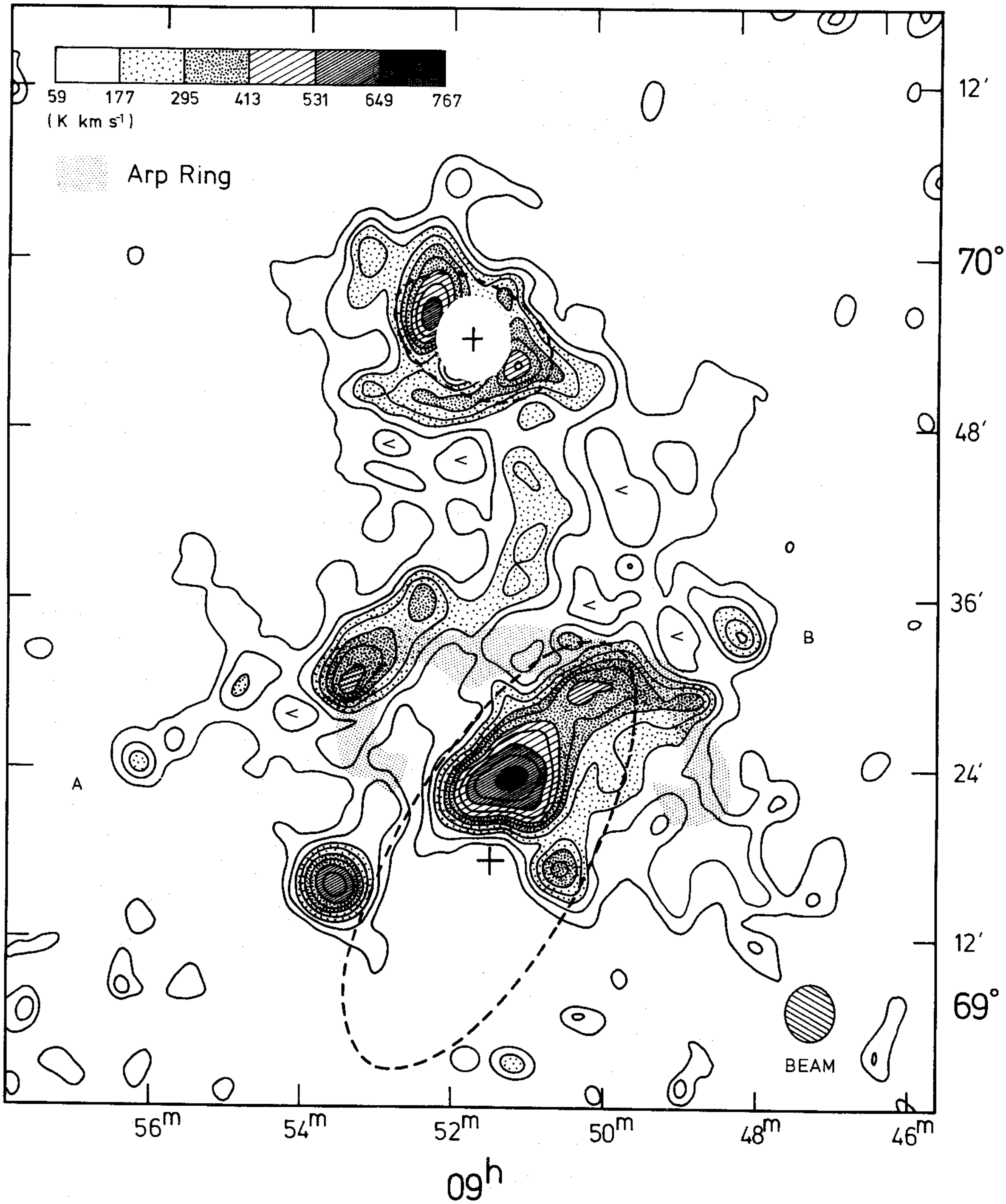

Figure 1. The low-resolution (4 arcmin) integrated hydrogen contour map with schematic representations of some optical features. The map does not include hydrogen with velocities less than +21 km/s. This cut-off has no effect on the map of the bridge or the distribution around M82 because no H I was detected in these regions at radial velocities lower than +21 km/s. The dashed ellipses correspond to the Holmberg dimensions of M81 and M82, respectively 35 × 14 and 13 × 8 arcmin. The upper cross is the position of the centroid of continuum emission in M82 ($\alpha_{1950.0}$ = 09h 51m 42s.63; $\delta_{1950.0}$ = 69° 55′2″.03), and the lower cross is the position of the nucleus of M81 given by van der Kruit (1974) ($\alpha_{1950.0}$ = 09h 51m 27s.2; $\delta_{1950.0}$ = 69° 18′08″.3). The faint Arp ring-feature is also indicated.

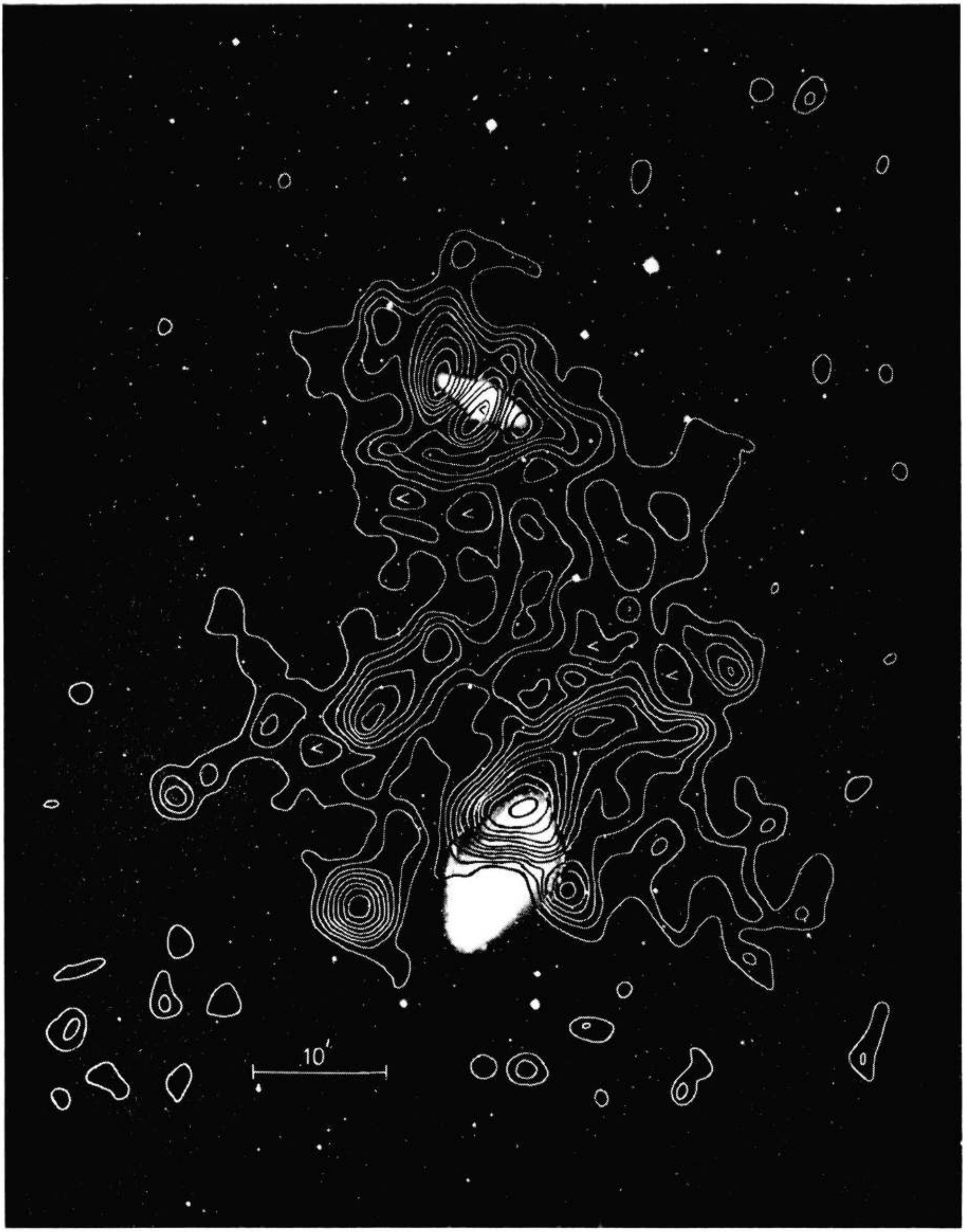

Plate 1. The low-resolution (4 arcmin) integrated hydrogen map superimposed on a red print of M81 (bottom) and M82 (top) taken from the Palomar Sky Survey Atlas. The apparent asymmetry of the H I content in M81 is caused by the low-velocity cut-off (21 km/s) of the velocity integral. The survey of M81 by Gottesman & Weliachew (1975) shows H I structure in the south of M81, including a diffuse outer 'spiral' arm which on the south-eastern side reaches down to a distance of ≈ 20 arcmin from the nucleus of M81. H I in front of the nucleus of M82 is not observable, and the size of this region is shown by the hole on Fig. 1 (Section 2). The 59 K km/s contour surrounding the galaxies has been added, and the rms noise is 24 K km/s at the map centre rising to 35 K km/s at the position of M81.

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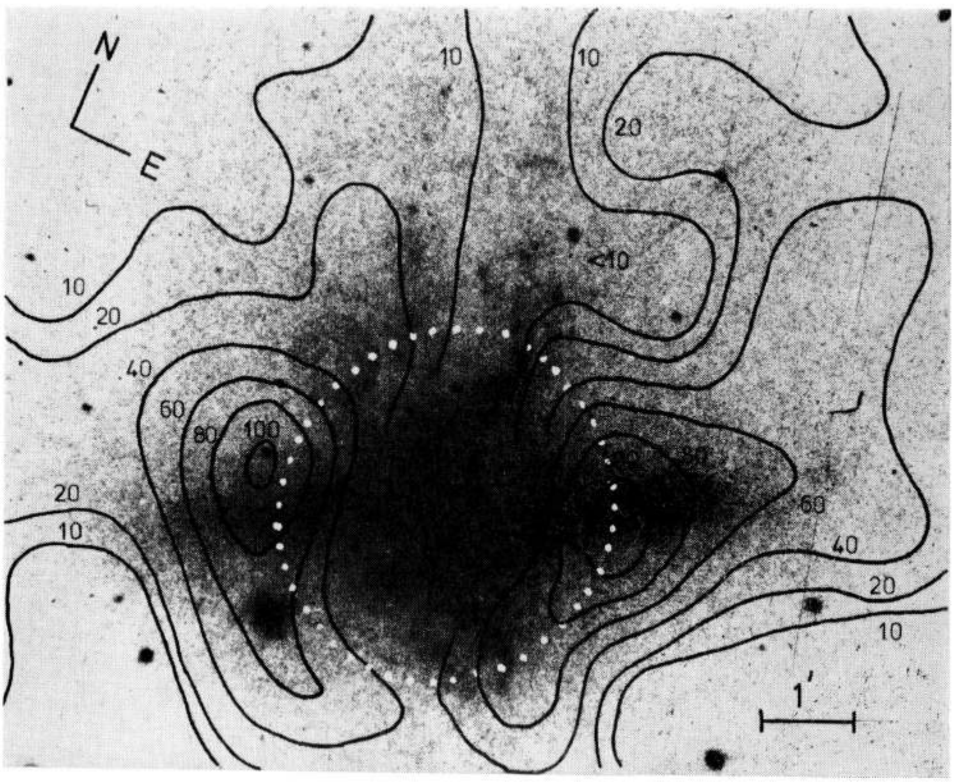

Plate 2. The high-resolution (2 arcmin) contour map of integrated hydrogen in M82 superimposed on an Hα photograph (courtesy J. M. Deharveng). H I emission from the area inside the dotted ellipse is unobservable because of contamination by absorption of the central source (Section 2). The map shows a diminution in the H I surface density in the direction of the north-eastern Hα filaments (compare Fig. 2). Contours are marked with percentages of the peak brightness, 1330 K km/s. Note the reversal of this plate.

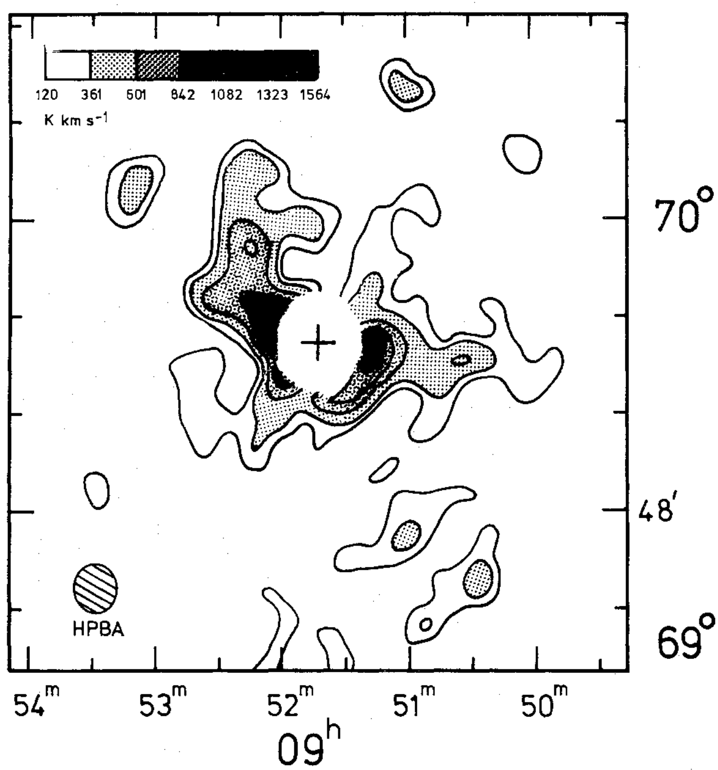

Figure 2. The high-resolution (2 arcmin) integrated hydrogen map of M82 with the same contour interval as in Plate 2. The central cross and 'hole' are respectively the continuum centroid position and full beam-area within which H I emission is unobservable. South of the nucleus some knots in the bridge can be seen. Rms noise is 41 K km/s at the map centre, and the contour interval is 132 K km/s.

defined by the Holmberg (1950) dimensions of the galaxies is $(10 \pm 1) \times 10^8 M_\odot$. The bridge contains a number of resolved H I clumps, the brightest of which coincides with the north-east limb of the ring-feature described by Arp (1965). A faint filamentary extension (marked A on Fig. 1) to this clump points towards the approximate position of NGC 3077 (≈ 70 arcmin from M82 in pa 145°, and ≈ 48 arcmin from M81 in pa 118°) which itself has an H I tail pointing towards M81 (Cottrell 1976). The similarity between the systemic velocity of NGC 3077 (15 ± 5 km/s) and that of the filamentary extension near the Arp feature (≈ 60 km/s) may mean that there is one continuous filament connecting the regions, but the present observations put an upper limit of ≈ 40 K km/s on its brightness. South of the optical ring, the bridge connects with a bright H I blob lying close to DDO 66, the Magellanic irregular companion to M81 (Rots & Shane 1974; Gottesman & Weliachew 1975). Gottesman & Weliachew's map of M81 shows that the bridge does not continue southwards of DDO 66 but merges into the H I associated with M81. The radial velocity map (Fig. 3) reveals a smooth, well-ordered velocity gradient in the bridge which, in the central part, has the value ≈ 5 km/s/kpc and extends over a projected distance ≈ 27 kpc.

3.1.3 The northern sector of M81

The present results may readily be compared with Gottesman & Weliachew's 2-arcmin survey, when allowance is made for the difference in angular resolution. In the region of overlap the two surveys agree on the general H I distribution and velocity field. On Fig. 1 there is a new discrete feature (marked B on Fig. 1) ≈ 28 kpc north-west of the nucleus of M81. This blob is divorced from the main body of H I in M81 and may be part of the tidal

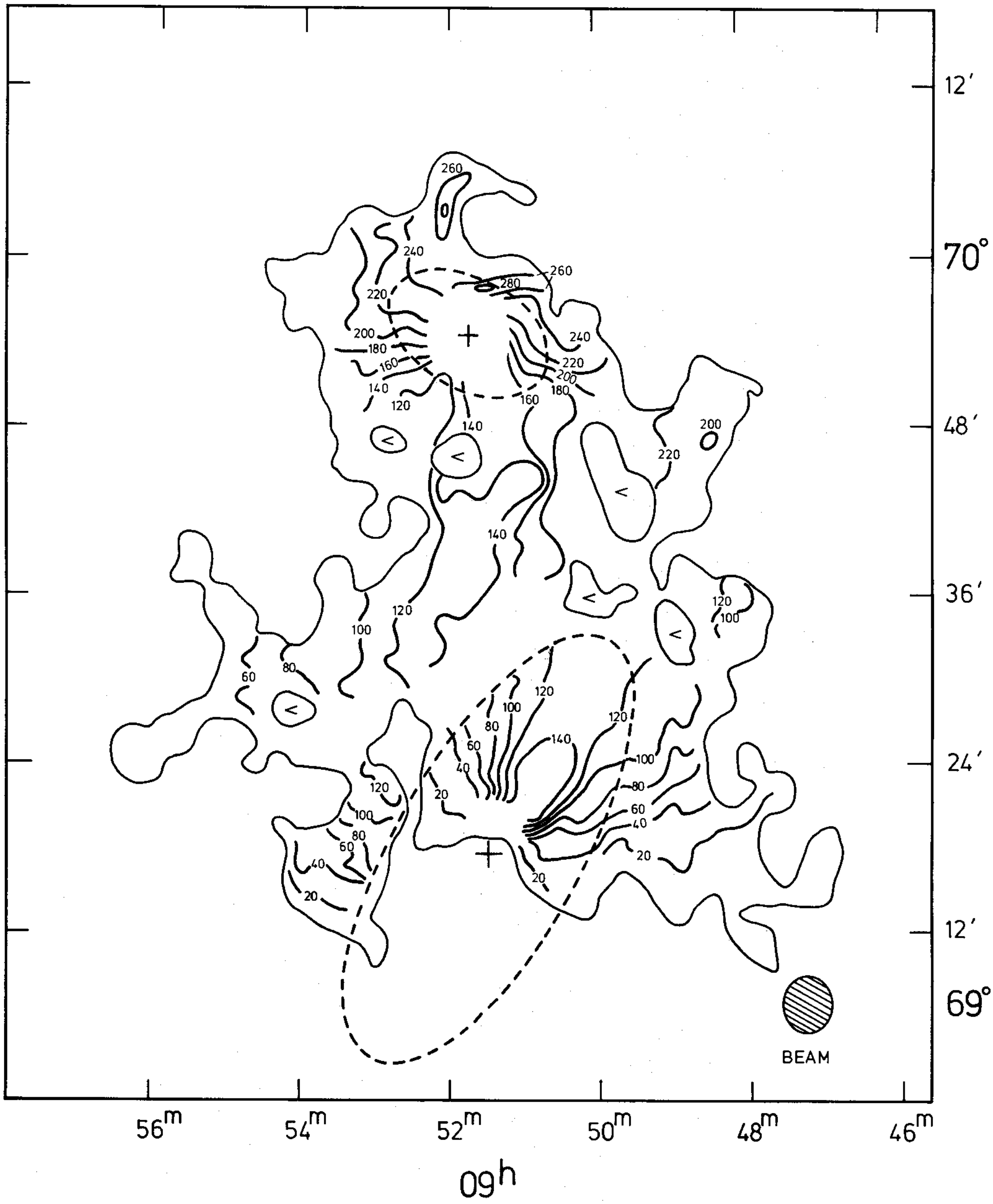

Figure 3. The low-resolution (4 arcmin) isovelocity map plotted inside the faint 59 K km/s H I contour surrounding the galaxies. The dashed ellipses and crosses are as in Fig. 1 and the rms noise is 6 km/s. Velocities are with respect to the Sun.

debris (Section 4.1). Although some of the H I in the bridge coincides with part of the Arp ring-feature, there is no clear evidence of coincidence elsewhere. In fact the brightest central parts of the ring (due north of the nucleus of M81) are associated with a *null* in the H I distribution.

3.2 THE RESULTS AT A RESOLUTION OF 2 ARCMIN

Plate 2 and Fig. 2 show an elongated H I source of size ≈12 × 8 arcmin approximately aligned

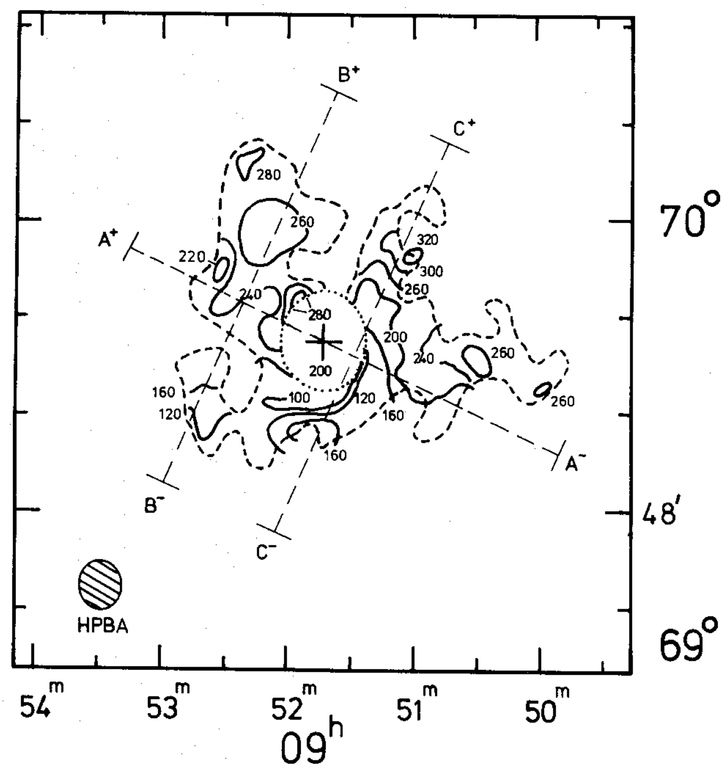

Figure 4. The high-resolution (2 arcmin) isovelocity map plotted inside the 120 K km/s H I contour surrounding M82. The dashed lines A^+A^-, B^+B^-, C^+C^- indicate the directions of 'cuts' through the field shown in Fig. 5. The dotted line is the full beam-area marked as in Fig. 2.

with the major axis of M82. The bright central condensations lie ≈ 3 arcmin (≈ 2.9 kpc) either side of the nucleus in position angle $\approx 75°$, close to the major axis. The central parts of the high-resolution integrated hydrogen map are shown superimposed on the deep Hα photograph (Plate 2) of Deharveng & Pellet (1970). It can be seen that there is a tendency for a diminution in the H I surface density along the northern minor axis of the galaxy, coinciding with the eastern half of the northern bundle of filaments. The lower-resolution integrated hydrogen map (Fig. 1) shows H I emission of peak brightness 295 K km/s at a distance of ≈ 4 arcmin from the nucleus on the northern half of the minor axis. There is no such feature on the high-resolution integrated H I map because, on all the single-channel maps made at the higher resolution, the brightness temperature of the H I at this position is lower than the noise gate (1.9 K) applied. The H I consequently absent from the high-resolution map has low surface brightness and a broader velocity profile than the surrounding H I. The results are inconclusive for the southern filaments because these do not protrude beyond the dotted boundary on Plate 2 within which H I emission cannot be measured. The coincidence of the H I minimum with the northern filaments provides evidence that the gas is actually above the plane of M82, and not a part of the bridge viewed in front of the galaxy. In this region on the continuum map there are no strong negative 'holes' which could have masked weak H I emission, and over the whole of the continuum map the negative sidelobes were in fact $\lesssim 4$ per cent of the main response. The limit to the integrated H I surface density in the direction of the north-eastern Hα filament is $\sigma_{\mathrm{H\,I}} < 2.2 \times 10^{20}$ atom cm^{-2}. The total H I mass (corrected for an optical depth of 0.1) inside the 2.2×10^{20} atom cm^{-2} contour surrounding the source is $(3.4 \pm 1) \times 10^8 M_\odot$. To the south-west of the nucleus some H I clumps belonging to the bridge can be seen.

The radial velocity field (Fig. 4) is complex, and to aid the location of general gradients

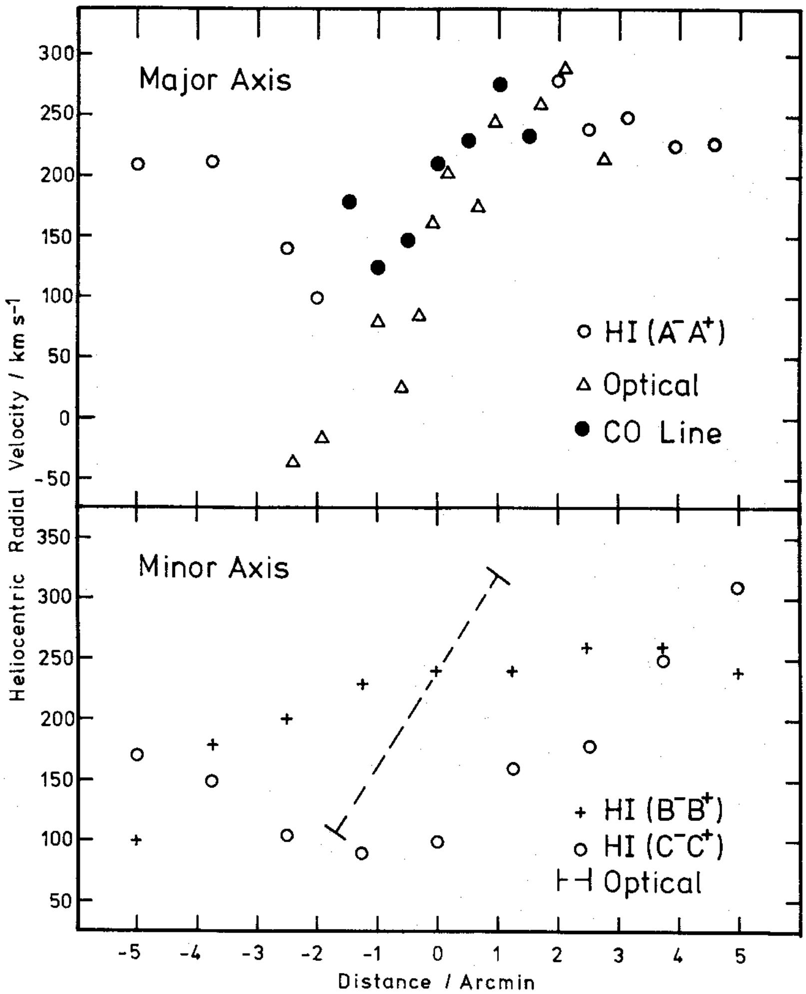

Figure 5. Plots of radial velocities measured along the cuts in Fig. 4, compared to optical and CO-line data (see text).

three cuts are presented in Fig. 5. The two cuts parallel to the minor axis (B^+B^- and C^+C^-) show that the radial velocities are higher to the north of the galaxy. Both of these cuts show a radial velocity gradient which is in the sense of that found optically in the filaments (marked as a dashed line in Fig. 5) by Lynds & Sandage (1963). Following Heckathorn (1972), the Lynds & Sandage data have been corrected to give a velocity of 240 km/s at the position of the nucleus.

Along the major axis the H I radial velocities (Fig. 5) reveal no systematic trend at distances $\gtrsim 3.5$ arcmin from the nucleus but, closer in, there is clear evidence for a gradient in the sense of both Mayall's (1960) optical rotation curve and Rickard's (1975) CO emission-line rotation curve, although it should be noted that there may be a systematic velocity error in Mayall's data (Heckathorn 1972) rendering it subject to vertical displacement in the diagram. In view of the high obscuration towards the nucleus of M82 (both Peimbert & Spinrad (1970) and van den Bergh (1971) have measured optical depths in the visual of ~ 3), the optical rotation curve may only be relevant to the outer (nearside) edge of the disc and not to the inner part where the 21-cm optical depth is ≈ 0.1 (Section 2). The gas outside 2.5 arcmin from the nucleus does not seem to be rotating in the disc, although it is moving with radial velocities $\approx 220 \pm 20$ km/s, close to the systemic velocity of the galaxy. It may be either bridge material or gas tidally captured from the outer parts of M81 (Section 4.1).

4 Discussion

4.1 THE INTERACTION

Two major pieces of evidence support the hypothesis that a close encounter has occurred between M81 and M82: (a) the galaxies are connected by a stream of neutral hydrogen which, at either end, merges into them with radial velocities close to their optical systemic velocities, and (b) Rots (1974) has found distortions in the radial velocity field of M81. The rotation curves measured to the north and south of M81 agree out to ≈ 10 kpc from the nucleus but beyond this the northern curve (facing M82) rises to high positive velocities, whereas the southern curve decreases monotonically. Rots attributed these anomalous velocities to tidal effects following a close passage of M82, Toomre & Toomre (1972) having already noted the 'openness' of M81's outer spiral structure as reminiscent of tidal effects in their model encounters. The maps of M81 by Gottesman & Weliachew (1975) show a faint outer H I spiral arm on the south of M81 (see their Figs 3 and 4) which reaches ≈ 20 arcmin south-west of the nucleus. There is no optical counterpart to this arm and it bifurcates at the tip. The arm may be a tidally induced counterarm of the type that Toomre & Toomre find commonly in their models.

Let us consider the geometry of the orbit:

(a) The *eccentricity* $e = (1 + 2\,\Sigma L^2/(GM)^2)^{1/2}$, where Σ is the specific total energy, L the specific angular momentum of orbiting body (identified with M82), and M the mass of central body (M81), assumed to be $1.1 \times 10^{11}\, M_\odot$ (Gottesman & Weliachew 1974). The projected separation and radial velocity difference for the pair are respectively 35 kpc and 271 km/s giving a *lower limit* on the eccentricity $e \gtrsim 4$, if most of the mass is in M81. The high eccentricity of the orbit implies that M82 is an intruder in the M81 group and has suffered a single close encounter with M81. Any model of the collision must therefore describe the formation of a H I streamer (of mass $\sim 10^9 M_\odot$), from disc material possibly originally belonging to M81, following a *single* passage rather than multiple encounters on a closed orbit.

(b) The upper limit on the *deflection angle*, $\Phi \lesssim \pi - 2\arccos(1/e)$, is 26°. If perigalacticon was on the south side of M81 then, from the geometry of an $e = 4$ orbit (shown in Fig. 6), M82 would have a large component of velocity in the plane of the sky in order for it to be in its present position relative to M81. This, in turn, would imply a much larger relative velocity between the galaxies and therefore a large value of e. Toomre & Toomre (1972) have noted the difficulty in making tidal bridges with high-eccentricity orbits and so, from this point of view, it is desirable to have a northern perigalacticon. Two other facts suggest a northern perigalacticon, namely (i) the anomalous H I velocities north of M81, (ii) the connection of the H I bridge to the north-eastern sector of the disc of M81.

(c) The *perigalacticon*, r_p, is related to the tidal radius, r_t, by von Hoerner's formula (King 1962), $r_t = r_p(m/3.5\,M)^{1/3}$, where M and m are respectively the masses of M81 and M82. If M82 were a gaseous disc, then material outside r_t would have been severely disturbed by the interaction. The present H I results (Section 3.2) show H I apparently rotating in the disc out to a radius ≈ 2.5 kpc, but beyond this the velocity field is chaotic. Taking $r_t = 2.5$ kpc and the mass of M82 as $10^{10} M_\odot$, we obtain $r_p \approx 9$ kpc. This value for the perigalacticon is approximately the radius at which Rots (1974) finds tidal effects in the disc of M81 to become important. Using this prescription for the orbital geometry, a schematic diagram of the proposed orbit is shown in Fig. 6. If the H I seen in directions above and below the plane of M82 is actually *in* the galaxy, a contention supported by the finding of an H I hole in the direction of the north-eastern filaments (see Sections 3.2 and 4.2), then the angular momentum of this material is approximately orthogonal to that of the disc but *parallel to the orbital angular momentum of M81 & M82.* This suggests that the gas above the plane of M82

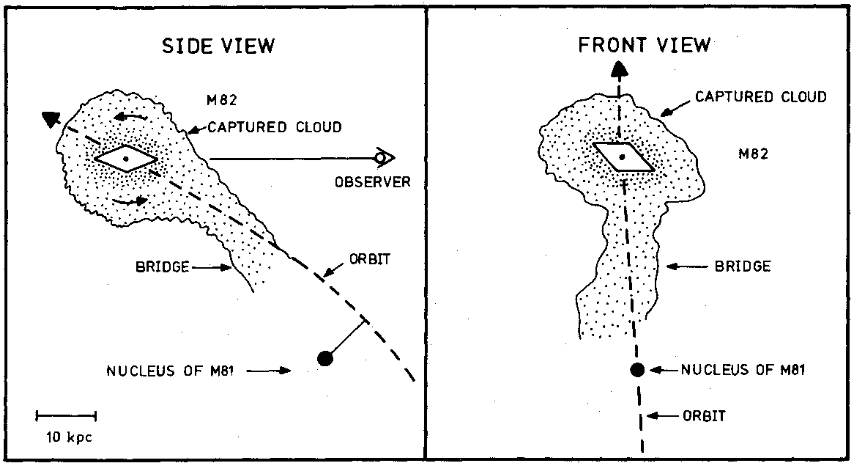

Figure 6. Schematic diagram of the proposed orbit of M82 following the prescription outlined in Section 4.2. Also sketched is the possible three-dimensional structure of the gas envelope surrounding M82 and the hydrogen bridge. The side view shows the spin of the gas cloud (arrows) about an axis aligned with the apparent major axis of M82 (front view). The angular momentum vector of the rotating cloud is approximately aligned with that of the orbital angular momentum of the interacting pair.

may be H I captured from the outer parts of M81 during the encounter. This gas is observed out to a distance ± 5 kpc from the plane of M82 where the escape velocity is ≈ 140 km/s. The gas at this distance is moving with $|V| \lesssim 120$ km/s with respect to the galaxy and may therefore be bound to it. The dynamics of this outer gas do not seem to be related in any way to those of the inner disc. Fig. 6 shows the possible three-dimensional structure of the gas envelope near M82 and the bridge in relation to the proposed orbit.

(d) The time since the encounter is difficult to estimate without a computer simulation. However, the assumption that the galaxies are separated by $\sqrt{2}$ of their *projected* separation implies a present separation of ≈ 50 kpc. This gives a time since perigalacticon of $\sim 1.8 \times 10^8$ yr, close to the time of $\sim 2 \times 10^8$ yr since the M81–NGC 3077 interaction (Cottrell 1976). Although the three galaxies are probably physically related, further understanding of the three-body problem is complicated by uncertainties in their true space positions and velocities.

4.2 THE FILAMENTS

The faint optical filaments (Plate 2) radiate both in Hα and the continuum, and were found by Lynds & Sandage (1963) to exhibit a radial velocity gradient. Correcting this for a large inclination of ~ 82°, they deduced that the gas was being expelled from the nucleus of M82 with velocities of 1000–2000 km/s, and postulated a violent explosion in the nucleus $\sim 10^6$ yr ago. The violent explosion models by Lynds & Sandage and Burbidge, Burbidge & Rubin (1964) assumed radiation *intrinsic* to the filaments, but Visvanathan & Sandage's (1972) observations revealing that both the narrow (~ 10 Å) Hα line and the continuum were highly (≈ 27 per cent) polarized led Sanders & Balamore (1971) to conclude that radiation from the filaments is light from a Seyfert-like nucleus scattered by dust. It follows that the observed Doppler shifts (≈ 100–200 km/s) of the Hα with respect to what is thought to be the systemic velocity of the M82 (240 km/s) (Heckathorn 1972; Weliachew 1974) are indicative of the *true* spatial velocities of the scattering dust, thus increasing the time since the explosion to $\sim 10^7$ yr. The southern filaments are *blueshifted* with respect to 240 km/s while those on the north are redshifted – possibly indicating a gas/dust flow towards the observer on the south and away from the observer on the north.

The present results reveal two new features: (a) a *diminution* of the H I surface-density towards the filaments on the north minor axis of M82, and (b) a radial velocity gradient of the H I surrounding the filaments in the same sense but of a different magnitude as that found in the filaments themselves.

These features suggest that the filaments are *embedded in and dynamically coupled to the outer neutral gas.* Dust particles in the filaments will behave like 'moving mirrors' giving an apparent Hα doppler shift which is a vector sum of their motions (i) in the line of sight and, (ii) with respect to the light source. However, the assumption that the dust clouds move with the neutral hydrogen allows us to solve for their true velocities in the plane containing dust, observer and light source. In view of the resolution of the present survey, a direct point-to-point comparison of the radio and the optical velocity fields is not yet possible.

It is of interest to consider why there is less H I in the vicinity of the filaments than elsewhere above the plane. Hargrave (1974) proposed a model of the filaments in which they were ejected from the nucleus by radiation pressure. This model suggests a natural interpretation of the observed H I hole as being a cavity formed in the surrounding neutral gas by radiation pressure acting on a plasma (ionized by nuclear radiation) via charged dust grains frozen in by magnetic fields.

If the mass of gas present in the filaments is 100 times that present in dust (typical for the plane of the Galaxy), then the effective mass of a grain subject to gravitational forces will be $m_g' = 100\, m_g$, where the mass of a dust grain, $m_g \sim 10^{-16}$ kg, has been calculated for dirty-ice particles of radius $r_g = 0.3\,\mu$m (Hargrave 1974) and specific density one. In the nuclear regions, Harper & Low (1973) estimate the total mass-to-infrared luminosity ratio as $(M/L)_{IR} < 0.001$ solar units. Therefor the ratio, η, of gravitational to radiation pressure forces close to the nucleus is $\eta = (M/L)_{IR}\,(4Gm_g' c/r_g^2) \sim 5 \times 10^{-2}$ and gravity will be unimportant. However, when the grain reaches ~ 4 kpc above the plane it will be subject to a much larger gravitational acceleration from the whole mass of the galaxy. If the total mass of M82 is $10^{10} M_\odot$ and the infrared luminosity $L = 2 \times 10^{37}$ W (Harper & Low 1973) $(M/L)_{IR} \approx 0.2$ implying $\eta \sim 10$, so gravity will be the dominant force on the grains beyond about 4 kpc from the nucleus. A complete solution to this problem clearly requires a knowledge of the gravitational potential in the *z*-direction, which is extremely uncertain.

However, the flow from the nucleus cannot be purely radial because this implies that the scattered light from the filaments would be redshifted *on both sides of the galaxy,* in contradiction with the observed blueshifts on the south side. To make blueshifts on the south side, the particles must have non-radial velocity components. The observed blueshifts are therefore explicable on the present model if the emergent plumes of gas/dust mixture collide with and are accelerated by the *outer* layer of neutral hydrogen which is rotating about the *major axis* of M82 (Section 4.1). The filaments can then acquire non-radial velocities in the right sense to give a blueshifted Hα line on the south side of the galaxy.

The time since the expulsion of the filaments in this model is essentially that suggested by Sanders & Balamore (1971), namely, ~ 10^7 yr, on the assumption of particle velocities ≈ 100–200 km/s. This is only ~ 1/20th of the estimated time since perigalacticon (~ 1.8×10^8 yr). Therefore we do not rule out models in which prolific star formation, required to explain the peculiarities in the nucleus of M82 (e.g. Hargrave 1974), has been triggered by the interaction.

In summary, it is possible that the holes in the H I distribution have been caused by the sweeping action of radiation pressure accelerating dust grains tied to plasma near the nucleus. But the dominant force on the plasma at large distances from the plane will be gravity, and a more detailed model will require a knowledge of the gravitational potential as a function of height above the plane. The observed blueshifts of the filaments are explicable on this model if the clouds of dust responsible for scattering the nuclear light have collided with and been accelerated by the outer rotating neutral hydrogen.

Conclusions

It is argued that M82 has tidally interacted with the north of M81 $\sim 1.8 \times 10^8$ yr ago, with perigalacticon ~ 9 kpc and orbital eccentricity ~ 4. The gas seen in directions above and below the disc of M82 shows a velocity field which, if interpreted as rotation about the *major axis*, has angular momentum in the same sense as the galaxy orbits and may be gas which has been captured from the outer parts of M81, and is now bound to and rotating about M82. Evidence of a diminution in the H I surface density along the northern minor axis coincident with the north-eastern Hα filamentary system supports the contention that the gas is actually above the plane of the galaxy and therefore must be related to the dynamics of the filaments. If the filaments are filled with charged dust particles and plasma frozen together by magnetic fields then, near the nucleus, radiation pressure from the infra-red source will be transmitted to the plasma by the dust and a 'hole' in the H I distribution will develop. As the filaments rise out to large distances from the nucleus, the dominant force on the plasma will be gravity due to the whole mass of the galaxy and the filaments will be decelerated. The model can explain observations of the blueshifted Hα line on the south side of M82 if the emergent plumes of gas/dust mixture have been accelerated by the outer rotating material.

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