A search for $\text{H}_2$ emission in bipolar nebulae and regions of interstellar shock

How to cite:

For guidance on citations see FAQs.

© 1985 European Southern Observatory

Version: Version of Record

Link(s) to article on publisher’s website: http://adsabs.harvard.edu/full/1985A&A...145..118P

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online’s data policy on reuse of materials please consult the policies page.

oro.open.ac.uk
A search for H$_2$ emission in bipolar nebulae and regions of interstellar shock

J. P. Phillips$^1$, G. J. White$^1$, and R. Harten$^2$

$^1$ Physics Department, Queen Mary College, Mile End Road, London E1 4NS, England
$^2$ Netherlands Foundation for Radio Astronomy, Oude Hoogeveensedijk 4, 7990 AA Dwingeloo, The Netherlands

Received June 18, accepted October 10, 1984

Summary. We report a H$_2$ emission survey of five bipolar outflow sources (NGC 1333, M2-9, As 353, S106, V645 Cyg), and one region of shock interaction between an H II region and molecular cloud (NGC 281). Two of the sources (M2-9, NGC 1333) were detected in the $v=1-0S(1)$, and $Q$ branch transitions of H$_2$, and we provide a detailed analysis and modelling for these cases. The probable mass of shocked H$_2$ is shown to range between 1.4 $\times$ 10$^{-6}$ and 4.2 $\times$ 10$^{-6}$ $M_\odot$ for M2-9, and $\approx$ 2.5 $\times$ 10$^{-4}$ and 1.9 $\times$ 10$^{-6}$ $M_\odot$ in the case of NGC 1333, although the latter values may require increasing by a factor of a few when due allowance is made for extinction. A detailed analysis for the core of M2-9 indicates that the ionised zone is extremely compact, and our Brackett line measures support other evidence in suggesting a high core expansion rate, large emission measure $E$ $\approx$ 4 $\times$ 10$^{16}$ cm$^{-6}$ pc, and a projected angular radius $\theta_e$ $\approx$ 0.04. Similarly, it is apparent from the H$_2$S(1) line strength that the core expansion velocity must be low and less than $\sim$ 1 km s$^{-1}$ (a constraint which is also required on dynamical grounds). Finally, CO $J=3-2$ observations of the source failed to detect emission above a 2$\sigma$ limit of $T_a$ $\approx$ 0.4 K, and this is shown to imply a probable expansion timescale $\lesssim$ 2 $\times$ 10$^3$ yr.

Key words: bipolar nebulae – infrared spectroscopy – H$_2$ emission

1. Introduction

Energetic bipolar outflow sources have recently been observed in association with a large proportion of both young and evolved stars (cf. Cohen, 1983; Lada, 1984). In the case of pre-main-sequence and young stellar outflows it appears that the mass flow is collimated by high density toroids and accretion discs, and similar structures may indeed be relevant to all categories of this phenomenon (cf. Konigl, 1982; Snell et al., 1980; Icke, 1981; Torrelles et al., 1983). The momentum outflow rate is frequently extremely large, of order $\sim$ 10$^{-3}$ to 10$^{-2}$ $M_\odot$ yr$^{-1}$ km s$^{-1}$ (corresponding to a total mechanical outflow energy $\sim$ 10$^{-10}$ $L_\odot$), some $\sim$ 10$^2$ to 10$^3$ times greater than can be accounted for through direct radiative acceleration alone; although multiple scattering of the emergent IR flux may increase momentum coupling in envelopes with high optical depth (Phillips and Beckman, 1980).

The velocities of the outflow material are similarly large, of order $\sim$ 10$^3$ km s$^{-1}$ for ionised gas and $\sim$ 10$^2$ km s$^{-1}$ for molecular flows. The interaction of this high velocity gas with ambient disc and placental material leads in turn to a wide variety of shock phenomena, including Herbig-Haro nebulosities, multiple optically thin CO line components (cf. Phillips et al., 1982), and enhanced H$_2$ quadrupole emission (cf. Simon and Joyce, 1983; Bally and Lada, 1982); although questions still remain concerning dissociation of H$_2$ at the high velocities relevant to these sources (Shull and Beckwith, 1982).

The H I masses associated with evolved stellar outflows are considerably lower than for protostellar sources, although many of the same phenomena appear also to occur in these cases. Outflow velocities are substantial (cf. Walsh, 1981; Meaburn and Walsh, 1980a), and the preferentially large central extensions in at least two nebulae (NGC 6302 and M2-9) may indicate the presence of similar toroidal collimating structures. The morphology of NGC 6302 is suggestive of an extended shock interface between neutral and ionised material (cf. Meaburn and Walsh, 1980b; Barral et al., 1982), and shocked H$_2$ quadrupole emission is seen in several such nebulae, including CRL 618, CRL 2688 (Beckwith et al., 1978; Thronson, 1981), and the core of NGC 6302 (Phillips et al., 1983). As we will see later, there is also evidence for centrally confined H$_2$ emission in M2-9. In short, the characteristics which distinguish pre- and post-main-sequence biconical nebulae are relatively few, and it is conceivable that several borderline cases may be mis-classified.

The incidence of relatively high levels of H$_2$ near-infrared emission in bipolar sources has prompted the present search for quadrupole lines in four young stellar outflows [NGC 1333 (HH7-11), As 353, S106, and V645 Cyg], a probable post-main sequence biconical structure (M2-9), and NGC 281, a region where an expanding H II zone appears to be interacting with an adjoining H I cloud. The measurements of NGC 281 employed a cooled grating spectrometer with a resolution $\lambda/\Delta\lambda = 273$, mounted on the United Kingdom Infrared Telescope in Hawaii (UKIRT), whilst the remaining sources were investigated with circular variable filter spectrometers at resolutions of 1% ($\lambda \sim 4$ $\mu$m) and 1.3% ($\lambda \sim 2$ $\mu$m). All spectra were calibrated using stars at similar elevations.

2. Discussion

Details of our results are provided in Table 1, together with various inferred parameters. In most cases molecular hydrogen was not detected to fairly low levels, and this permits relatively stringent upper limits to be placed on the masses of shocked H$_2$. For this purpose we have generally taken

$$\frac{M(H_2)}{g_f h \nu_{v_1} 4\pi D^2} = Q(T_e) e^{-\nu_{v_1} X_r} H_{v_1} F_{v_1} 4\pi D^2,$$  \[1\]
Table 1. Summary of observations

<table>
<thead>
<tr>
<th>Source</th>
<th>α (H:M:S)</th>
<th>β (°:′:″)</th>
<th>Bν, W·cm⁻²</th>
<th>Bα, W·cm⁻²</th>
<th>H₂S(1), W·cm⁻²</th>
<th>H₂ CO, 2.15 μm Continuum, W·cm⁻²</th>
<th>Beam Arcsecs</th>
<th>Distance kpc</th>
<th>M(H₂) Te=10³K</th>
<th>M(H₂) Te=2·10³K</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC281</td>
<td>00:49:28.8</td>
<td>+56:17:35</td>
<td>-</td>
<td>-</td>
<td>&lt;1.4·10⁻¹⁰</td>
<td>-</td>
<td>5.4</td>
<td>2.1</td>
<td>&lt;7.5·10⁻⁷</td>
<td>&lt;1.2·10⁻⁸</td>
</tr>
<tr>
<td>NGC1333</td>
<td>03:25:58.2</td>
<td>+31:05:46</td>
<td>-</td>
<td>-</td>
<td>&lt;2.2·10⁻¹⁰</td>
<td>6.2·10⁻¹⁰ 1.4·10⁻¹⁷</td>
<td>12</td>
<td>0.55</td>
<td>2.5·10⁻⁴</td>
<td>1.9·10⁻⁵</td>
</tr>
<tr>
<td>12°N</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&lt;1.3·10⁻¹⁰</td>
<td>&lt;4.7·10⁻¹⁹</td>
<td>12</td>
<td>0.55</td>
<td>&lt;5.1·10⁻⁵</td>
<td>&lt;3.9·10⁻⁶</td>
</tr>
<tr>
<td>12°S</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&lt;8.0·10⁻¹¹</td>
<td>&lt;2.9·10⁻¹⁹</td>
<td>12</td>
<td>0.55</td>
<td>&lt;3.2·10⁻⁵</td>
<td>&lt;2.4·10⁻⁶</td>
</tr>
<tr>
<td>12°W</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&lt;1.2·10⁻¹⁰</td>
<td>&lt;5.0·10⁻¹⁹</td>
<td>12</td>
<td>0.55</td>
<td>&lt;4.7·10⁻⁵</td>
<td>&lt;3.6·10⁻⁶</td>
</tr>
<tr>
<td>12°E</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&lt;1.2·10⁻¹⁰</td>
<td>&lt;3.1·10⁻¹⁹</td>
<td>12</td>
<td>0.55</td>
<td>&lt;4.7·10⁻⁵</td>
<td>&lt;3.6·10⁻⁶</td>
</tr>
<tr>
<td>M2-9</td>
<td>17:02:52.6</td>
<td>-10:04:31</td>
<td>1.8·10⁻¹⁹</td>
<td>8.1·10⁻¹⁹</td>
<td>7.1·10⁻¹⁹</td>
<td>-</td>
<td>8</td>
<td>1.0</td>
<td>1.4·10⁻⁶</td>
<td>4.2·10⁻⁸</td>
</tr>
<tr>
<td>8°N</td>
<td>-</td>
<td>-</td>
<td>&lt;4.6·10⁻¹⁰</td>
<td>-</td>
<td>&lt;4.6·10⁻¹⁰</td>
<td>-</td>
<td>8</td>
<td>1.0</td>
<td>&lt;8.9·10⁻⁸</td>
<td>&lt;2.7·10⁻⁹</td>
</tr>
<tr>
<td>AS 353</td>
<td>19:18:08.0</td>
<td>+10:56:20</td>
<td>&lt;2.9·10⁻¹⁰</td>
<td>-</td>
<td>&lt;2.9·10⁻¹⁰</td>
<td>-</td>
<td>12</td>
<td>0.15</td>
<td>&lt;8.0·10⁻⁹</td>
<td>&lt;1.2·10⁻¹⁰</td>
</tr>
<tr>
<td>20°E5°S</td>
<td>&lt;6.6·10⁻¹⁰</td>
<td>-</td>
<td>&lt;6.6·10⁻¹⁰</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>0.15</td>
<td>&lt;1.8·10⁻⁸</td>
<td>&lt;2.8·10⁻¹⁰</td>
</tr>
<tr>
<td>S106</td>
<td>20:25:33.8</td>
<td>+37:12:52</td>
<td>4.2·10⁻¹⁸</td>
<td>-</td>
<td>&lt;4.0·10⁻¹⁸</td>
<td>-</td>
<td>12</td>
<td>0.5</td>
<td>&lt;1.2·10⁻⁶</td>
<td>&lt;1.9·10⁻⁸</td>
</tr>
<tr>
<td>30°N</td>
<td>-</td>
<td>-</td>
<td>&lt;3.7·10⁻¹⁰</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>0.5</td>
<td>&lt;1.1·10⁻⁷</td>
<td>&lt;1.8·10⁻⁹</td>
</tr>
<tr>
<td>V645 CYG</td>
<td>21:38:10.6</td>
<td>+50:00:43</td>
<td>&lt;1.2·10⁻¹⁹</td>
<td>-</td>
<td>&lt;1.2·10⁻¹⁹</td>
<td>-</td>
<td>12</td>
<td>6.0</td>
<td>&lt;5.3·10⁻⁵</td>
<td>&lt;8.2·10⁻⁷</td>
</tr>
<tr>
<td>12°S</td>
<td>&lt;5.6·10⁻²⁰</td>
<td>-</td>
<td>&lt;5.6·10⁻²⁰</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>6.0</td>
<td>&lt;2.5·10⁻⁵</td>
<td>&lt;3.8·10⁻⁷</td>
</tr>
</tbody>
</table>
indicate high levels of shock compression (Israel and Felli, 1978; Bally and Scoville, 1982). Our spectrum of this source however shows no strong evidence for $H_2$ emission, although $B$ is clearly seen above a strong dust continuum (Fig. 1). In this respect, our results confirm the low-resolution spectra of Eiroa and Hefele (1983), and the very much higher resolution spectra of Tokunaga and Thompson (1979). As 355 by way of contrast appears to represent a very much less massive structure centred on a probable T-Tauri star. The CO outflow lobes range in velocity up to $\sim 13 \text{ km s}^{-1}$, implying a mass loss rate $\sim 7 \times 10^{-8} M_\odot \text{ yr}^{-1}$ (Edwards and Snell, 1982). The presence of such high mass outflows is extremely difficult to account for with our present suite of mass ejection models (DeCampli, 1980), although the absence of $H_2$ is in line with a previous survey of such stars by Beckwith et al. (1978a), which showed detected emission in only one out of five measured T-Tauri.

$V645$ Cyg appears to represent a significantly more massive and luminous ($\sim 10^6 L_\odot$) star of spectral class $\sim 09V$. The CO outflow extends over a velocity range $\sim 15 \text{ km s}^{-1}$ (Rodriguez et al., 1981), which corresponds to a momentum outflow rate $\geq 2 \times 10^{45} \text{ erg}$ (Rodriguez et al., 1982). The powering source is associated with a star-like condensation N0 (Harvey and Lada, 1980), which is in turn joined by the polarised reflecting nebulae N1 and N2 (Cohen, 1977). Our measuring aperture was centred upon N0, but we again detected no mass of shocked $H_2$ exceeding $\sim 5 \times 10^{-2} M_\odot$. A spectrum for the 12S position is illustrated in Fig. 2.

Finally, NGC 281 was measured with a CGS at the position of the maser found by Elmegreen and Lada (1978). This region has been discussed in detail by both Elmegreen and Lada (1978) and Elmegreen and Moran (1979). CO line profiles, visual imaging, maser activity, and a range of other evidence points to high levels of local $H_2$ compression, triggered star formation, and shock activity, although our measurements again failed to detect the $H_2S(I)$ $2.1 \mu \text{m}$ line above a $2\sigma$ significance level of $1.4 \times 10^{-20} \text{ W cm}^{-2}$, implying correspondingly low masses of shock heated gas.

M2-9 and NGC 1333 were respectively detected in the $V = 1 - 0 S(I)$ and $Q$ branch transitions of $H_2$, and we discuss the implications of these results in Sect. 3 and 4.

3. NGC 1333

The region of NGC 1333 is widely strewn with Herbig-Haro nebulosities, and newly formed and forming stars. $Q$ branch $H_2$ emission was detected in association with the maser HH7-11 A (Haschick et al., 1980), which may (within errors) also coincide with the infrared point source SSV13 (Sandell and Olofsson, 1981; Cohen and Schwartz, 1983). Directed towards this is a line of nebuloieties HH7-11 which have already been found by Simon and Joyce (1983) to have strong associated $H_2S(I)$ emission. Two other masers (B and C) are also located in the vicinity of the source, at the edge of a dense $NH_3$ condensation $\sim 2'$ across, and it is clear that we are witnessing extensive local star-formation, and a widespread and complex interaction between stellar outflows and the local molecular material. Whilst the overall dynamics of this region are quite clearly far from simple (Haschick et al., 1980), the alignment of HH7-11 with SSV13 (HH7-11A) and a bipolar molecular outflow source (Snell and Edwards, 1981) is suggestive of a common causative link, as noted by Cohen (1982). It is probable that a stellar wind outflow is again being directed into a biconical configuration, with consequent extensive shock activity.

© European Southern Observatory • Provided by the NASA Astrophysics Data System
Our spectrum for the source is illustrated in Fig. 5, where the Q branch emission is seen to be superimposed on a relatively strong and slowly rising continuum. From Kwan (1977) we note that for a pre-shock density \( n_0 \), and shock velocity \( V_s \), the S(1) line strength is approximately given through

\[
S(1) = 3 \times 10^{-3} n_0^{1/3} (n_0/10^5)^{2.3} (V_s/24 \text{ km s}^{-1})^{-1.7} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1},
\]

where the comparatively shallow variation of \( S(1) \) with \( V_s \) results from partial collisional dissociation of \( \text{H}_2 \) between \( V_s \sim 15 \text{ km s}^{-1} \) and \( V_s \sim 25 \text{ km s}^{-1} \). Since the corresponding model Q branch intensity \( \Sigma Q \) [which covers the \( V = 1 \rightarrow 0 \) (Q1), (Q2), and (Q3) lines] is of order \( \sim 1.4 S(1) \), it can be readily shown that

\[
\frac{dM}{dt} = 9.6 \times 10^{-37} (V_s/24 \text{ km s}^{-1})^{-0.7} \Sigma Q M_\odot \text{ yr}^{-1}
\]

for a spherical shock outflow, where \( dM/dt \) is the rate of mass influx into the shock. This influx must in turn match the ram pressure of the stellar wind (velocity \( V_c \)), and it follows that the stellar wind mass-loss rate is then given through

\[
\frac{dM_w}{dt} = 1.1 \times 10^{-8} \left( \frac{D}{\text{kpc}} \right)^2 \left( \frac{V_c}{V_w} \right)^{-0.7} \Sigma Q \text{ cm}^{-2} \text{ s}^{-1} \text{ yr}^{-1},
\]

where \( \Sigma Q \) is the extinction corrected flux at Earth, and \( D \) is again source distance.

Assuming \( V_c \approx 20 \text{ km s}^{-1} \), \( D = 0.55 \text{ kpc} \), and \( V_c/V_w \sim 10^{-2} \), then results in a mass-loss rate \( dM_w/dt \sim 2 \times 10^{-7} M_\odot \text{ yr}^{-1} \). Note, however, that this estimation is a lower limit, and does not account for extinction. Similarly, it does not apply for material escaping into the bipolar flow, which is presumably responsible for the more widespread (and possibly less extincted) emission of Simon and Joyce. Although the precise dynamics of this region are therefore speculative, the observed levels of \( \Sigma Q \) are reasonably in accord with those expected for a standard spherical shock and source outflow model, for which mass-loss rates are comparable to those of other, similar nebulae.

Some indication that overall levels of extinction may be quite substantial is provided through the \( \Sigma Q/S(1) \) upper limit ratio. Our present observations imply \( \Sigma Q/S(1) \geq 2.8 \), significantly greater than predicted by shock models [the results of Kwan (1977) can be shown to imply \( \Sigma Q/S(1) \geq 1.4 \), and Hollenbach and Shull (1977) suggest values \( \geq 2.1 \text{--} 1.6 \) for \( V_s \) between 6 and 14 \( \text{km s}^{-1} \)]. Extinction corrected measures of this ratio vary from 1.9 for NGC 7027 (Smith et al., 1981), to 1.75 for OM C1 (Davis et al., 1982), and if we adopt a mean value \( \langle \Sigma Q/S(1) \rangle \approx 1.8 \), then the observed upper limit for NGC 1333 would require \( A_o \approx 28.2 \text{ mag} \) (note that atmospheric features are unlikely to strongly compromise either the present values of \( \Sigma Q \), or the comparative estimates for NGC 7027 or OM C1, all of which were taken at altitudes where the relevant telluric lines are weak. Similarly, although the nearby maser HH7-11 B does appear to be associated with a highly compact, weak radio continuum source, no similar emission has been observed in association with HH7-11 A (Haschick et al., 1980). In consequence, contamination of our results by H1 20 - 5 through 22 - 5 is likely to be negligible). There are other indications that extinction towards the central IR source is reasonably high. C^18O mapping by Schwartz et al. (1983) indicates a local hydrogen column density

\( N(\text{H}_2) \sim 4 \times 10^{21} \text{ cm}^{-2} \), implying \( A_o \sim 4 \text{ mag} \), although the peak in \( N(\text{H}_2) \sim 6 \times 10^{21} \text{ cm}^{-2} \) occurs approximately 2' to the northeast of this source. This rather low value for \( A_o \) almost certainly reflects the large (diffraction limited) beamsize of 65'' employed for these measures. Infrared spectroscopy (Cohen and Schwartz, 1983) by way of contrast shows a clear silicate absorption feature, which would at a minimum suggest \( A_o \approx 11 \text{ mag} \) (for \( A_o/\text{mag} \sim 12 \); and no appreciable emission from the absorbing grains). More realistic modelling for power-law (\( n \propto r^{-\beta} \)) grain density distributions has been outlined by Mitchell and Robinson (1981), and these imply an outer dust shell radius \( \gtrsim 10^3 R_4 \) (where \( R_4 \) is the stellar radius), given an inner grain temperature \( T_g \sim 10^3 K \). The corresponding 1 \( \mu \)m extinction would then range between \( \tau = 20 \) and \( \tau \approx 70 \) for \( 1 < \beta < 2 \). It is entirely conceivable therefore that the large value of \( \Sigma Q/S(1) \) is due to appreciable levels of extinction, and that the estimates of \( M(\text{H}_2) \) and \( dM_w/dt \) must be correspondingly jumped-up by a factor of a few.

Having said this, it may be noted that a U.V. cascade model (cf. Black and Dalgarno, 1976) would predict a ratio \( \Sigma Q/S(1) \sim 2.8 \) - very close to our upper limit. Similarly, our observations imply a parametric ratio

\[
\Gamma = \frac{Q(1) + 2Q(2) + 3Q(3) - 0.33Q(7) + Q(6)}{Q(4) + 5Q(5) - 0.67Q(7) + Q(6)} \sim 1.4 \pm 0.3,
\]

which would be quite at variance with a simple shock excitation mechanism. Our own calculations show that \( \Gamma \) varies from 5.8 through to 2.8 for values of \( T_g \), ranging from \( 10^3 \text{ K} \) to \( 3 \times 10^3 \text{ K} \), and similar values are also predicted by the various shock models; from Kwan (1977) we determine \( \Gamma \approx 2.8 \). The Q-branch profile appears rather anomalous, therefore, and it would be interesting to see confirmatory measures.

4. M2-9

M2-9 is an extremely interesting nebula passing through what appears to be an early stage of post-main sequence evolution. Several authors have pointed to characteristics indicative of a protoplanetary structure, whilst its morphology is suggestive of a type I nebula with high shell mass \( M_s \sim 1 \sim 2.5 M_\odot \); note however that the nitrogen abundance would then be anomalously low (Peimbert and Torres-Peimbert, 1983). The central star has not been observed, although from photon counting procedures Calvet and Cohen (1978) adduce \( L_\gamma \gtrsim 844 (D/\text{kpc})^2 L_\odot \), and a spectral type of \( (\text{at minimum}) \sim \text{BIV} \). As in the case of NGC 6302, the spectral lines show evidence of a lower velocity primary emission component, and line wings extending out to \( \sim 250 \text{ km s}^{-1} \) and possibly further (Walsh, 1981). From this it seems possible that compact (and conceivably neutral) nebular components are being wind-driven by a high velocity stellar outflow. Perhaps the most unusual features of this source, however, are the massive Balmer decrement, leading to a ratio \( \text{H}_\alpha/\text{H}_\beta \sim 30 \), and a predilection for short term variations in the outer nebular structure (Allen and Swings, 1972; van den Bergh, 1974). We will discuss these properties further in the ensuing analysis.

Using measures of the Balmer decrement Calvet and Cohen (1978) found a central extinction \( A_o \sim 5.35 \pm 0.3 \) mag, significantly higher than in the wings \( (A_o \sim 2.7 \text{ mag}) \), and this difference is also graphically illustrated in the published spectra of Swings and Andrillat (1979). Polarisation maps have been produced by Lacasse (1982) and King et al. (1981), and these show a relatively straightforward pattern of grain scattering outside the primary
condensations, and a collar of maximum polarised intensity between 4° and 10° from the centre. A tendency for the polarisation vectors to become parallel to the radius in at least one condensation may reflect the influence of larger grain species (cf. Martin, 1978). Either way, a substantial proportion of the polarised light is reflected directly from the (otherwise obscured) central core, whilst forbidden-line radiation primarily emanates from the less dense wings (Schmidt and Cohen, 1981).

Figure 3 shows our spectrum for the source, characterised by a steeply rising dust continuum with colour temperature 825 K — similar to the photometric estimate of Cohen and Barlow (1974). Superimposed on this are the $\alpha$ and $\gamma$ hydrogen Brackett lines, the $\nu=1-0$($S(1)$) transition of molecular hydrogen, and (blended with $B\gamma$) the high excitation 7–10 transition of H$\alpha$. The $S(1)$ line is seen rather more clearly in Fig. 4, where we have subtracted an 825 K blackbody continuum. Note that, as for NGC 6302 (Phillips et al., 1983), no emission is seen immediately outside of the core, and this suggests that appreciable shock activity may be confined to a relatively small central volume.

In what follows, we use both present and previously published results to provide a detailed evaluation of the central source structure, and from this the characteristics of the shocked H$_2$ zone. We also discuss observations of M2-9 in the $J=3-2$ transition of CO and, briefly, the dynamics of both neutral and ionised mass components.

4.1. The structure of the inner core

There are several lines of evidence to indicate that the ionised core of M2-9 can be no more than $\sim$0.1 in diameter; a factor $\sim$500 times smaller than the optically observed lobes. This ionised zone is in turn surrounded by a 5.5 diameter volume of (probably neutral) material, which collimates the flow, and is observed through scattering as a bright central nebulous. Since the primary arguments favouring such a scenario have not previously been brought together into a single discussion, we provide a detailed analysis below:

4.1.1. Core-size estimate based on radio continuum

From the combined radio continuum measures of Milne and Aller (1982, 1975), Purton et al. (1978), and Marsh et al. (1976), it is clear that the source is probably optically thick over a frequency range $\nu \leq 14.7$ GHz. If a core-halo analysis similar to that of Ohnion (1975) and Panagia and Felli (1975) is adopted, in which density varies with radius $r$ as

$$n_\nu (r) = n_0 \left( \frac{r}{R_*} \right)^{-\beta}, \quad r > R_*, \quad (5a)$$

$$n_\nu (r) = n_0 \left[ \frac{r}{R_*} \right]^{-\beta}, \quad r \leq R_*, \quad (5b)$$

then the relatively shallow spectral index $\alpha = 0.5 \pm 0.2$ would imply a corresponding $\beta = 1.9 \pm 0.2$ (for both spherically symmetric and biconical halo structures). The turn-over frequency $\nu_\gamma$ and flux $S_\nu$ for such a scenario are given through

$$\log S_\nu = 4.486 + \log \left[ \frac{T_e^2}{D^2} \frac{2n_0 R_*^2 v_{\nu}^2}{2 \pi} \right], \quad (6a)$$

$$\log \nu_\gamma = -0.516 + \frac{1}{2.1} \log \left[ \frac{8}{3} \frac{T_e^{1.35} n_0 R_*}{v_{\nu}^2} \right], \quad (6b)$$

where $\nu_\gamma$ is in GHz, $S_\nu$ in Janskies, $T_e$ is the electron temperature, and $R_*$ and $D$ are in parsecs. Taking the observed flux at 14.7 GHz (Milne and Aller, 1982) to represent a lower limit to $S_\nu$, we then find values $E = 2n_0 R_* > 6.4 \times 10^4$ cm$^{-6}$ pc, and a projected angular radius $\theta < 0.08$ for the core. From these relations it also follows that $7.7 \times 10^4 \lesssim 2n_0 R_* \lesssim 6.4 \times 10^4$ pc for $D = 1$ kpc, whence $n_0 \gtrsim 1.1 \times 10^4$ cm$^{-3}$. Note that although the model used here may not have detailed applicability to M2-9, the limits on $\theta$ and $E$ are reasonably secure.

A corresponding analysis for the type I bipolar NGC 6377 and NGC 6302 leads to respective core size estimates of 20, 0.3 and 2.3; again very much smaller than the full extent of optical nebulous, but agreeing well with the radio maps of Terzian et al. (1974) and Felli and Perinotto (1979). The H$\beta$/radio flux ratios similarly imply values of $A_v$, which are substantially greater than would be deduced from the Balmer decrements, and this may indicate preferentially high levels of core extinction. Taking these and other correspondences into account, therefore, it is clear that the structure of M2-9 is by no means unique, and has indeed all the hallmarks of typical type I source (although see also our later comments concerning nebular mass).

4.1.2. Brackett lines

The ratio of Brackett $\alpha$ to Brackett $\gamma$ (allowing for $A_v = 5.3$ mag of central extinction) is found from our present results to be $\sim 3.4$;
some 20% greater than would be predicted for case B (high density limit, $T_e \approx 10^4$ K; Giles (1977) and Osterbrock (1974)). This level of disagreement is commensurate with the relative calibration uncertainties between 2 and 4 $\mu$m. Since H$\alpha/H$B $\approx 0.10$ [from the published spectra of Swings and Andrilat (1979) and Schmidt and Cohen (1981)] and [H$\beta$] $\approx 2.3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (Milne and Aller, 1975), then we obtain $[\text{Br}$-$\gamma]/[\text{H}$] $\approx 7.95$ (where we have used H$\alpha$ in preference to H$\beta$, since there is some evidence that H$\beta$ may be significantly self-absorbed). This compares with an expected intrinsic ratio $\approx 0.10$, and implies an extinction $A_V \approx 3.7$ mag; very much smaller than usually assumed. This is hardly surprising, however, since the measured H$\beta$ flux includes contributions from the lobes.

Given that the Brackett $\gamma$ flux is given through

$$F(\text{Br}$-$\gamma) = 6.6 \times 10^{-27} [\text{Br}$-$\gamma/\text{H}$] [\text{H}$]/[\text{H}$] \sigma_\text{F} \text{erg cm}^{-2} \text{s}^{-1}$$

for an optically thin sphere very much smaller that the beam, subtending a solid angle $\sigma_\text{F}$, then we obtain a radius $\theta_\text{F} \approx 0.041$, and an emission measure $E \approx 4 \times 10^{10}$ cm$^{-6}$ pc for $D \approx 1$ kpc, and $n_e \approx 10^{-7}$ cm$^{-3}$.

4.1.3. Core rotation

Allen and Swings (1972) and van den Bergh (1973) have noted that the extremely rapid structural changes in M2-9 may arise from rotation of the central dust core, and consequent variations in the emergent U.V. flux. From the work of Kohoutek and Surdej (1980) we determine an apparent angular rotation rate of $\Omega \approx 1.9 \times 10^{-9}$ rad s$^{-1}$, and assuming rotational equilibrium of the inner core and a stellar mass $\approx 2.5 M_\odot$ [characteristic of type I sources (Renzini and Voli, 1981)], then the angular radius of the rotating envelope must be $\approx 0.03$ at 1 kpc.

It is perhaps worth noting at this point that Kohoutek and Surdej (1980) argue for rotation of the entire nebula, out to a distance $\approx 15''$ from the central star. This appears to be implausible on dynamical grounds, however. If for instance we assume the ad hoc, and exceptionally small, local distance of $\approx 50$ pc promoted by these authors, a total mass of $\approx 2.7 \times 10^4 M_\odot$ would be required for gravitational stability; quite outside the normal range for evolved nebulae. Increasing the distance to 1 kpc (the value of $D$ adopted here) has the effect of increasing the required stabilising mass by a further factor of $\approx 10^4$.

Note that the value of $D$ employed both here and in the rest of this analysis is based on the discussion of Calvert and Cohen (1978). This is by no means entirely secure, although a factor $\approx 2$ variation either way would not severely undermine present conclusions.

4.1.4. Radius of the inner Stromgren sphere

Calvert and Cohen (1978) have used photon-counting procedures to deduce a total central star luminosity $L_\ast > 844 (D/kpc)^2 L_\odot$, and a spectral class of (at minimum) BIV. The total Lyman continuum photon flux for such a star would be $\approx 3.3 \times 10^{35} \text{s}^{-1}$ (Panagia, 1973), which would in turn lead to a Stromgren sphere with $n_e^2/3 \approx 4.4 \text{ cm}^{-2} \text{pc}$. Given again that $n_e \approx 10^{7}$ cm$^{-3}$, then we obtain $\theta_\text{F} \approx 0.02$ arcseconds and $E \approx 1.9 \times 10^{10}$ cm$^{-6}$ pc.

This radius, whilst confirming the small central core size, is nevertheless significantly smaller than found from the B$\gamma$ results. This also applies to the emission measure $E$, and it is clear (irrespective of uncertainties in $n_e$) that the central star spectral type must be significantly earlier ($\approx$ B0.5V) than assumed above.

Such a revision is also supported by Walsh (1981) on the basis of mass flow properties.

4.1.5. Infrared flux

If the observed IR continuum reflects a range of grain temperatures (i.e., there is a temperature gradient throughout the central $5.5$ nebosity) and excesses at 1.65 $\mu$m are taken to arise from grains with temperature $\approx 1300$ K (close to silicate sublimation temperatures), then for grains with radius $a \approx 10^{-4}$ $\mu$m, mean Planck volume emissivity $\phi(T_{\mu\nu}, \alpha)$, and U.V. absorptivity $Q_{\mu\nu} = 1$, the inner radius of the dust shell occurs at

$$R_{\mu\nu} \approx \left[ \frac{3 L_\ast}{64 \pi a^3 T_{\mu\nu}^4} \right]^{1/2}$$

If, following Aitken and Roche (1982), we further presume a silicate grain composition (i.e., $\varepsilon \approx 10^3$; Gilman, 1974), then for a B0.5V irradiating star we derive $\theta_\text{F} \approx 0.056 (D/kpc)^{-1}$. On this basis, the bulk of short wave ($\lambda \leq 3.6$ $\mu$m) emission would be expected to arise from an extremely small central region, and this is indeed observed; Allen and Swings (1972) find 2 $\mu$m emission to predominantly derive from the central $\approx 12$% volume of the $5.5$ core.

4.1.6. High resolution mapping

Bignell (1983) has recently published a 1.46 GHz high resolution map of M2-9 taken with the VLA. This is reasonably in accord with the analysis above, and shows the central core to have a radius no greater than 0.05.

Taking all these estimates together, it is clear that a consistent picture emerges of a high emission measure core of extremely small volume. Whilst certain parameters in the analysis (such as $n_e$ and $D$) are not very closely defined, the core radius almost certainly lies within a factor $\sim 1.5$ of $R_{\mu\nu} \approx 0.05$, with material near the inner boundary of this core ultimately responsible for the observed variations in outer shell structure. This is in turn enveloped by a region with mean harmonic diameter $5.5$ which, although its nature is not entirely clear, is in all probability neutral. The U.V. extinction through this zone must be of order $\sim 1$ mag at $\lambda \approx 0.1$, for instance, and the attenuation of Lyman continuum would be correspondingly severe. Similarly, an ionised zone would be expected to evolve at sonic velocities, and this degree of instability would lead to very poor outflow collimation over extended time periods (assuming the usual model for bipolar formation).

The high density of the central core can be shown to imply a large H$\alpha$ optical depth $\tau(\text{H}$A$) \approx 1.4 \times 10^{-30} n_e^2 R_{\mu\nu}$, (Kaplan and Pikeln, 1970), for which circumstance substantial Balmer self-absorption would also occur. This possibility has similarly been noted by other investigators in an attempt to explain the observed lower order members of the Balmer series. The observed values of H$\alpha$/H$\beta$ and H$\beta$/H$\gamma$ are also consistent with a value $\tau(\text{Ly}$A$) \approx 10^4$ appropriate for an ionisation bounded core (Cox and Mathews, 1969), although uncertainties and errors in the decrement preclude a more detailed analysis. Finally, from these ratios and the analysis of Gerola, Salem, and Panagia (1971), it is apparent that collisional ionisation from the ground state must be small, and can contribute no more than $\approx 10$% to the total ionisation rate.

As in the cases of NGC 6302 (Phillips, Reay, and White, 1983) and NGC 7027 (Treffers et al., 1976) the HeII 7–10 transition at $\lambda \approx 2.19 \mu$m appears to be relatively strong, although blended at
Fig. 5. Near-infrared spectrum for NGC 1333 (HH7-11A). The Q branch emission is seen to be superimposed upon a strongly rising dust continuum, although there is no corresponding evidence for S branch emission.

Fig. 6. Schematic representation (not to scale) of the M2-9 core zone. The outflow wind interacts with (and accelerates) neutral condensations in the lobes, whilst the primary H₂ emission is confined to an extremely small core shock zone.

These resolutions with By. The prevalence of both H₂S(1) and HeI 7-10 in all three of these sources is indeed quite striking, and may represent a useful diagnostic signature for type I objects taken generally. This characteristic is perhaps not entirely surprising when account is taken of the probable shared characteristics of these sources, which include a wide range of excitations, high H₁ masses, and substantial stellar winds. Rather more extraordinary is the complete absence of enhanced HeI 2S-2P at λ ∼ 2.06 μm. This is strongly present in both NGC 7027 and NGC 6302, and might have been similarly expected in M2-9 as a consequence of dense core, and the (probable) high Lyα optical depth (Thompson and Tokunaga, 1980).

The overall picture emerging from this work is illustrated in Fig. 6. Given a normal value of A_v(N(H₂)+0.5N(H)) ∼ 10⁻²¹ mag cm², the central 5':5 collimating zone would then have a mass ∼ 0.1 M☉, and the 0.1 core ionised mass would be ∼ 1.5 x 10⁻³ M☉; values not unreasonable for a protoplanetary nebula, but appreciably smaller than might have been expected for a type I object (1-2.5 M☉; Renzini and Voli, 1981). Given a mean lobe density n_e ∼ 2 x 10⁴ cm⁻³ (Walsh, 1981) we also estimate an ionised mass ∼ 1.7 x 10⁻³ M☉ for the wings alone. The extinction in the lobes for a normal value of A_v/N(H) would then be A_v ∼ 0.1 mag; significantly short of the 2.7 mag observed. It appears likely therefore that up to 2.6 mag of nebular extinction is due to foreground (interstellar) material, a conclusion which would also be consistent with the relatively large value of D (∼ 1 kpc) assumed here.

Note, however, that there is some evidence in other planetary nebulae for depressed values of A_v/(N(H₂)+0.5N(H)) compared to the interstellar medium. If this is also true of M2-9, then the masses derived above may be substantially too low, and a type I status cannot therefore be entirely precluded.

4.2. Properties of the H₂ emission zone

If the H₂ emission in M2-9 is taken to arise near the interface of the H₁ and HII zones – that is, in a very small central volume of inner radius ∼ 0.05″ – then we obtain an S(1) radiative rate ∼ 6.0 erg cm⁻² sr⁻¹ s⁻¹. The rate of heat input into the shock for a pre-shock density n₀, and shock velocity Vₛ is given by n₀Vₛ²/(2μ₁ MᵥVₛ²). If this now equated with the S(1) radiative rate quoted above (a severe lower limit to the total cooling), then we obtain n₀ ≥ 6.7 x 10⁶ cm⁻³ for Vₛ = 15 km s⁻¹; that is, the H₂ would be appreciably thermalized.

Under these circumstances a more accurate expression for the S(1) line strength is given through Eq. (2), and this yields a surprisingly high pre-shock density n₀ ≥ 2 x 10⁷ cm⁻³. Such a large (and probably unrealistic) value for n₀ argues in turn for significantly lower values of Vₛ (and this is also required on dynamical grounds; see later). For Vₛ = 2 km s⁻¹, for instance, the requisite n₀ would be reduced by ∼ two to three orders of magnitude, to a point where the H₂ is barely thermalized.

The relevance of a U.V. cascade model for H₂ excitation is not easy to assess, although there are two lines of evidence which probably rule out such an hypothesis for M2-9. In the first place, the S(1) V = 2-1 line at λ = 2.248 μm would be expected to be relatively strong for such a mechanism, of order ∼ 0.55S(1) V = 1-0, which would not be the case for collisional enhancement (Black and Dalgarno, 1976; Black et al., 1981). We observe a 2σ upper limit S(1) V = 2-1/S(1) V = 1-0 ≤ 0.26. Perhaps rather more crucially, however, the model for U.V. pumping which comes closest to representing present circumstances is that of Black (1978) for NGC 7027, in which molecules are excited by a 10⁷ K radiation field with dilution 1.2 x 10⁻¹⁴. Scaling this model to M2-9, we find that a B0.5V star with L ∼ 2 x 10⁵ L☉ would produce an S(1) flux considerably less than observed here; or, putting this another way, the observed S(1) flux would require irradiation by a star with L ∼ 2 x 10⁷ L☉. Some caution is required here since the central star in M2-9 is neither as evolved nor as hot as for NGC 7027, and other nebular parameters probably also differ somewhat. Nevertheless, it appears likely that a U.V. cascade mechanism would be too inefficient for present purposes.

Isaacman (1984) has pointed to a third possible test involving the strength of V = 1-0S(2) at λ ∼ 2.035 μm, which he argues should be relatively weak for N.U.V. cascade models. However, models by Black et al. (1981) in which associative detachment and U.V. pumping (by a 10⁷ K radiation field) predominate, imply a ratio V = 1-0S(2)/V = 1-0S(1) ∼ 0.42. This is barely different from the predictions of a shock model (Hollenbach and Shull (1977) suggest S(2)/S(1) = 0.27 to 0.39 for a velocity range Vₛ = 6-14 km s⁻¹), and given that at least two of the nebulae considered by Isaacman have Zanstra temperatures comparable to or greater than ∼ 10⁵ K, the detection of S(2)/S(1) = 1-0 by this author does not appear to definitively preclude U.V. pumping. Certainly, the absence of V = 1-0S(2) in M2-9 is consistent with either model, since noise levels are relatively high.
and the probable small shock velocity $V_s$ relevant for this source implies a correspondingly low $V = 1 - 0 S(2)$ intensity.

4.3. CO observations of the central core

Given that the central dust may have a temperature as high as $\sim 400$ K, based on the colour temperature of the 10 $\mu$m continuum (Cohen and Barlow, 1974), and assuming the CO to be optically thick, then a 1° diffraction limited beam would detect CO lines at the $T_R \sim 40$ K level. With this prospect in mind we therefore investigated the $J = 3 - 2$ CO spectrum of this source in September 1983, using the QMC submillimetre wave receiver mounted on UKIRT. The measured beamsize was 55°, and the resulting spectrum is illustrated in Fig. 7. It is seen that no source is present at the source radial velocity above a 2σ limit of $\sim 0.4$ K; presumably implying that either the excitation temperature has been grossly overestimated, or the source is optically thin. Given that line optical depth for the $J = J - 1$ rotational transition is given through

$$\tau = \frac{3.45 \times 10^{-15}(J + 1)e^{-5.54(J + 1)} e^{-5.54(J + 1)}}{e^{-5.6(J + 1)} - e^{-5.54(J + 1)}} N(12CO) \Delta V T_{ex} \tag{9}$$

for a large velocity gradient (LVG) model in which $N(12CO)$ is the CO column density, then if a more conservative CO excitation temperature $T_{ex} \sim 100$ K is adopted [based on FIR IRAS photometry for other planetary sources; Pottasch (1983)], we obtain a velocity range through the 55° core of $\Delta V \lesssim 12$ km s$^{-1}$ (where we again assume a central $A_v \sim 2.6$ mag, and adopt $A_v / N(H_2) \sim 10^{-21}$ mag c$^{-2}$, $N(12CO) / N(H_2) \sim 10^{-4}$). This implies a plausible expansion timescale $\tau_{exp} \lesssim 2 \times 10^5$ yr.

It is interesting in this context to note that Walsh (1981) finds splitting of the central Hz line which would suggest expansion at velocity $\sim 30$ km s$^{-1}$. Given the small size of central core, the expansion timescale then becomes inordinately short, of order $\sim 8$ yr. It is likely therefore that the observed Hz profiles result from components of the outflow jets orientated along the line of sight, as illustrated in Fig. 6. The outflow electron density $n_e$ subsequently declines as $r^{-2}$, from an initial value $\sim 10^3$ cm$^{-3}$, to the typical densities $\sim 10^3$ cm$^{-3}$ observed by Walsh (1981) outside of the main condensations ($\sim 10^9$ from the core). The central (ionised) core itself must clearly be expanding rather slowly (at no more than $\sim 0.1$ km s$^{-1}$, say), and it is interesting to envisage the possible dynamics of such a region.

For this purpose we shall assume that an expanding ionised core of radius $R_c$ sweeps up a neutral envelope of mass

$$M_S = M_0 \left[ \frac{R_S}{R_0} \right]^{6}, \tag{10}$$

where $M_0$ and $R_0$ are a fiducial mass and radius. For a momentum input from the stellar wind $V_{out} dM/dt$, the equation of motion is then given through

$$R^2 \frac{dV}{dR} + \beta R^3 V_s - V_0 \frac{dM}{dt} \tag{11}$$

for which the simplest analytical solution with varying $M$, is given by $\beta = 1$. This yields $V^2 = (V/R_0 dM/dt)/M_0$, for $R_0 = R_1 V_0$, where $R_1$ is the initial radius of expansion, and for $V \sim 1$ km s$^{-1}$, $dM / dt \sim 10^{-7} M_0$ yr$^{-1}$, $R_1 = R_0 = 7.5 \times 10^4$ cm, and $V_0 \sim 250$ km s$^{-1}$, we then find $M_0 / M_0 \sim 10^{-3}$, and an expansion period $\approx 2.5 \times 10^5$ yr.

Whilst the model above has a purely pedagogical value, it is clear that a relatively modest size for the ionised core does not conflict with properties of the central region (insofar as these are at present understood), or indicate an implausible nebular age.

5. Conclusions

We have searched for H$_2$ emission in five bipolar outflow sources, and one zone of shock interaction between an HII region and molecular cloud (NGC 281). The results for most nebulae were negative, and demonstrated extremely low upper-limit masses of shocked H$_2$, ranging from $M(H_2) < 10^{-10} M_\odot$ for As 353, to a few times $10^{-8} M_\odot$ for V645 Cygni. Between 2.5 $10^{-4}$ and $1.9 \times 10^{-5} M_\odot$ of H$_2$ appears to be present in NGC 1333 (given $10^{21} K \lesssim T_{ex} \lesssim 2 \times 10^5$ K), although these estimates are probably somewhat low because of extinction. The observed Q branch emission level is shown to be reasonably consistent with a model of mass outflow in which $dM / dt \sim 2 \times 10^{-7} M_\odot$ yr$^{-1}$, and $V_0 \sim 10^3$ km s$^{-1}$; parameters typical of other, similar sources. The mass of H$_2$ in M2-9 lies probably between 4.2 $10^{-8} M_\odot$ and $1.4 \times 10^{-6} M_\odot$, estimated for the $V = 1 - 0 S(1)$ line, and appreciable Hen 7-10 $\lambda = 2.19$ $\mu$m emission is also observed. A detailed analysis using several lines of evidence demonstrates that most HII emission arises in an extremely restricted core volume, and this probably also implies a high H$_2$ emission rate and low pre-shock velocity; a U.V. cascade model can probably be discarded for this source. No $J = 3 - 2$ CO detection was detected above a 0.4 K level, and this is shown to be reasonably consistent with deduced source properties, given a normal interstellar value of $A_v / N(H_2)$, and an expansion timescale $\tau_{exp} \lesssim 2 \times 10^5$ yr. The levels of extinction derived from the higher order members of the Balmer series are broadly confirmed by the By and Bz line measures, which may in turn indicate masses $M_N \sim 0.1 (10^{-21} [N(H_2) + 0.5 N(H)] / A_v) M_\odot$ for the ionised and neutral regions combined. Such low values of $M_N$ would preclude classification as a type I nebula for normal I.S. mass absorption coefficients, and this presumption is also supported by the relatively low nitrogen abundance in this source. Morphological similarities to other type I nebulae however argue persuasively to the contrary, and the status of this object, whether type I, or protoplanetary, or perhaps even both, remains quite unresolved.

Acknowledgements. We are extremely grateful for help and assistance from Richard Wade, Peredur Williams, and the UKIRT staff.
References


