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A search for H₂ emission in bipolar nebulae and regions of interstellar shock

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Summary. We report a H₂ 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 H₂, and we provide a detailed analysis and modelling for these cases. The probable mass of shocked H₂ is shown to range between $1.4 \cdot 10^{-6}$ and $4.2 \cdot 10^{-8} M_{\odot}$ for M2-9, and $\approx 2.5 \cdot 10^{-4}$ and $1.9 \cdot 10^{-5} M_{\odot}$ 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 extinction, large emission measure $E \sim 4 \cdot 10^{10} \text{ cm}^{-6} \text{ pc}$, and a projected angular radius $\theta_c \sim 0''.04$. Similarly, it is apparent from the H₂S(1) line strength that the core expansion velocity must be low and less than $\sim 1 \text{ km s}^{-1}$ (a constraint which is also required on dynamical grounds). Finally, CO $J=3-2$ observations of the source failed to detect emission above a 2σ limit of $T_R^* \sim 0.4 \text{ K}$, and this is shown to imply a probable expansion timescale $\lesssim 2 \cdot 10^3 \text{ yr}$.

Key words: bipolar nebulae – infrared spectroscopy – H₂ 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 $\sim 10^{-1}$ to $10^{-3} M_{\odot} \text{ yr}^{-1} \text{ km s}^{-1}$ (corresponding to a total mechanical outflow energy $\approx 10-10^3 L_{\odot}$), some $\sim 10^2-10^4$ 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 $\sim 10^3 \text{ km s}^{-1}$ for ionised gas and $\sim 10^2 \text{ km s}^{-1}$ 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 H₂ quadrupole emission (cf. Simon and Joyce, 1983; Bally and Lada, 1982); although questions still remain concerning dissociation of H₂ at the large 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 extinctions 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 H₂ 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 H₂ 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 H₂ 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, S 106, and V 645 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% ($\lambda \sim 4 \mu\text{m}$) and 1.3% ($\lambda \sim 2 \mu\text{m}$). 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 H₂. For this purpose we have generally taken

$$M(\text{H}_2) = \frac{Q(T_{\text{ex}}) e^{E_u/KT_{\text{ex}}} M_{\text{H}_2} F_{u1} 4\pi D^2}{g_J h \nu_{u1} A_{u1}}, \quad (1)$$

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Table 1. Summary of observations

Source	α H:M:S	δ °:':"	B _y W.cm ⁻²	B _x W.cm ⁻²	H ₂ S(1) W.cm ⁻²	H ₂ ΣQ W.cm ⁻²	2.15 μ m Continuum W.cm ⁻² μ m ⁻¹	Beam Arcsecs	Distance kpc	M(H ₂) Tex ⁻² 10 ³ K	M(H ₂) Tex ⁻² 10 ³ K
NGC281	00:49:28.8	+56:17:35	-	-	<1.4.10 ⁻²⁰	-	-	5.4	2.1	<7.5.10 ⁻⁷	<1.2.10 ⁻⁸
NGC1333	03:25:58.2	+31:05:46	-	-	<2.2.10 ⁻²⁰	6.2.10 ⁻²⁰	1.4.10 ⁻¹⁷	12	0.55	2.5.10 ⁻⁴	1.9.10 ⁻⁵
		12°N	-	-	-	<1.3.10 ⁻²⁰	<4.7.10 ⁻¹⁹	12	0.55	<5.1.10 ⁻⁵	<3.9.10 ⁻⁶
		12°S	-	-	-	<8.0.10 ⁻²¹	<2.9.10 ⁻¹⁹	12	0.55	<3.2.10 ⁻⁵	<2.4.10 ⁻⁶
		12°W	-	-	-	<1.2.10 ⁻²⁰	<5.0.10 ⁻¹⁹	12	0.55	<4.7.10 ⁻⁵	<3.6.10 ⁻⁶
		12°E	-	-	-	<1.2.10 ⁻²⁰	<3.1.10 ⁻¹⁹	12	0.55	<4.7.10 ⁻⁵	<3.6.10 ⁻⁶
M2-9	17:02:52.6	-10:04:31	1.8.10 ⁻¹⁹	8.1.10 ⁻¹⁹	7.1.10 ⁻¹⁹	-	6.2.10 ⁻¹⁷	8	1.0	1.4.10 ⁻⁶	4.2.10 ⁻⁸
		8°N	<4.6.10 ⁻²⁰	-	<4.6.10 ⁻²⁰	-	-	8	1.0	<8.9.10 ⁻⁸	<2.7.10 ⁻⁹
AS 353	19:18:08.0	+10:56:20	<2.9.10 ⁻²⁰	-	<2.9.10 ⁻²⁰	-	-	12	0.15	<8.0.10 ⁻⁹	<1.2.10 ⁻¹⁰
		20°E5"S	<6.6.10 ⁻²⁰	-	<6.6.10 ⁻²⁰	-	-	12	0.15	<1.8.10 ⁻⁸	<2.8.10 ⁻¹⁰
S106	20:25:33.8	+37:12:52	4.2.10 ⁻¹⁸	-	<4.0.10 ⁻¹⁹	-	1.35.10 ⁻¹⁶	12	0.5	<1.2.10 ⁻⁶	<1.9.10 ⁻⁸
		30°N	-	-	<3.7.10 ⁻²⁰	-	-	12	0.5	<1.1.10 ⁻⁷	<1.8.10 ⁻⁹
V645 CYG	21:38:10.6	+50:00:43	<1.2.10 ⁻¹⁹	-	<1.2.10 ⁻¹⁹	-	-	12	6.0	<5.3.10 ⁻⁵	<8.2.10 ⁻⁷
		12°S	<5.6.10 ⁻²⁰	-	<5.6.10 ⁻²⁰	-	-	12	6.0	<2.5.10 ⁻⁵	<3.8.10 ⁻⁷

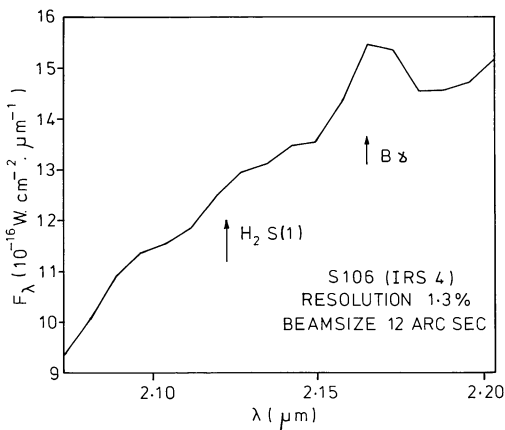


Fig. 1. 2.1 μm CVF spectrum for S106, showing strong B_γ and dust continuum

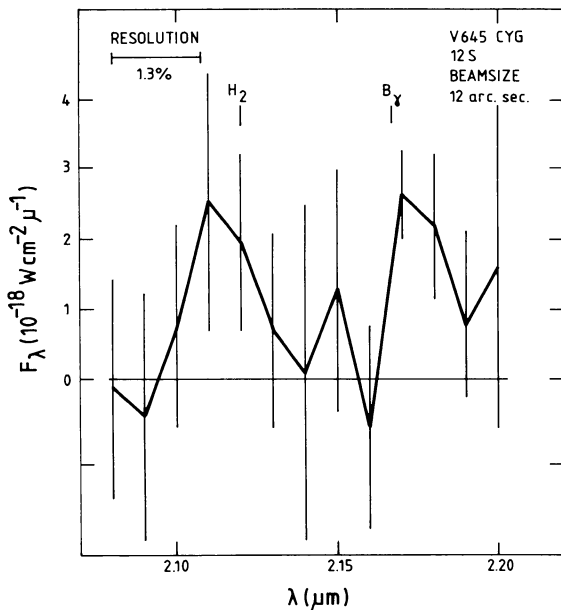


Fig. 2. Spectrum of V645 Cyg for the 12S position. No significant line features are detected in this source at present sensitivities

where T_{ex} is the excitation temperature, $Q(T_{ex})$ is the partition function, E_u is the energy of the upper state, ν_{ul} is the line frequency and A_{ul} is the spontaneous emission rate out of the upper state. F_{ul} is the total line flux at Earth for a source at distance D , and the level statistical weight g_J takes a value $3(2J+1)$ for odd J , and $(2J+1)$ for even J (for an ortho to para ratio of 3:1).

The excitation temperatures $T_{ex} = 10^3$ K and $2 \cdot 10^3$ K in Table 1 span the typical observed range in other sources (cf. Isaacman, 1984; Scoville et al., 1982; Gautier et al., 1976; Smith et al., 1981). Corrections for extinction were included for M2-9 alone; in other sources the appropriate value for A_v is more speculative, although the resultant upper limit estimates of $M(\text{H}_2)$ are unlikely to be more than a factor of a few too low.

S106 is an extremely well studied bipolar source powered by a B0V–08V star with luminosity $L \sim 10^4 L_\odot$. In this case the collimating disk appears to be large and well resolved by $J=1-0$ CO and ^{13}CO mapping, which imply a total mass $\sim 10^2 M_\odot$ (Bally and Scoville, 1982). The present observations are centred on the exciting star in a region close to the interface of HII and H I zones, where CO and radio continuum observations

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_γ 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 353 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 $\sim 7 \cdot 10^{-8} M_\odot \text{ yr}^{-1}$ (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 (De Campli, 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-Tauris.

V645 Cyg appears to represent a significantly more massive and luminous ($\sim 10^6 L_\odot$) star of spectral class $\sim 09\text{V}$. The CO outflow extends over a velocity range $\sim 15 \text{ km s}^{-1}$ (Rodríguez et al., 1981), which corresponds to a momentum outflow rate $\gtrsim 2 \cdot 10^{45} \text{ erg}$ (Rodríguez et al., 1982). The powering source is associated with a star-like condensation N0 (Harvey and Lada, 1980), which is in turn adjoined 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 $\sim 5 \cdot 10^{-5} M_\odot$. A spectrum for the 12" S 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 I compression, triggered star formation, and shock activity, although our measurements again failed to detect the $\text{H}_2\text{S}(1)$ 2.1 μm line above a 2σ significance level of $1.4 \cdot 10^{-20} \text{ W cm}^{-2}$, implying correspondingly low masses of shock heated gas.

M2-9 and NGC 1333 were respectively detected in the $V=1-0$ S(1) 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 nebulosities HH7-11 which have already been found by Simon and Joyce (1983) to have strong associated $\text{H}_2\text{S}(1)$ 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.

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

$$S(1) = 3 \cdot 10^{-3} (n_0/10^5) \cdot (24/V_s)^{-1.7} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \quad (2)$$

where the comparatively shallow variation of $S(1)$ with V_s results from partial collisional dissociation of H₂ between $V_s \sim 15 \text{ km s}^{-1}$ and $V_s = 25 \text{ km s}^{-1}$. Since the corresponding model Q branch intensity ΣQ [which covers the $V=1-0$ $Q(1)$, $Q(2)$, and $Q(3)$ lines] is of order $\sim 1.4 S(1)$, it can be readily shown that

$$\frac{dM}{dt} = 9.6 \cdot 10^{-37} (V_s/24 \text{ km s}^{-1})^{-0.7} \Sigma Q M_\odot \text{ yr}^{-1} \quad (3)$$

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_w), and it follows that the stellar wind mass-loss rate is then given through

$$\frac{dM_w}{dt} = 1.1 \cdot 10^8 \left[\frac{D}{\text{kpc}} \right]^2 \left[\frac{V_s}{V_w} \right] \cdot \left[\frac{V_s}{24 \text{ km s}^{-1}} \right]^{-0.7} \frac{\text{OBS}}{\Sigma Q} M_\odot \text{ yr}^{-1}, \quad (4)$$

where $\frac{\text{OBS}}{\Sigma Q} \text{ erg cm}^{-2} \text{ s}^{-1}$ is the extinction corrected flux at Earth, and D is again source distance.

Assuming $V_s \approx 20 \text{ km s}^{-1}$, $D = 0.55 \text{ kpc}$ and $V_s/V_w \sim 10^{-2}$, then results in a mass-loss rate $dM_w/dt \sim 2 \cdot 10^{-7} M_\odot \text{ yr}^{-1}$. Note, however, that this estimation is a lower limit, and does not account for extinction. Similarly, it does not allow for material escaping into the bipolar flow, which is presumably responsible for the more widespread (and possibly less extinguished) emission of Simon and Joyce. Although the precise dynamics of this region are therefore speculative, the observed levels of ΣQ 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 $\Sigma Q/S(1) \sim 1.4$, and Hollenbach and Shull (1977) suggest values $\sim 2.1-1.6$ for V_s between 6 and 14 km s^{-1}]. Extinction corrected measures of this ratio vary from 1.9 for NGC 7027 (Smith et al., 1981), to 1.75 for OMC1 (Davis et al., 1982), and if we adopt a mean value $\Sigma Q/S(1) \sim 1.8$, then the observed upper limit for NGC 1333 would require $A_v \geq 28.2 \text{ mag}$ (note that atmospheric features are unlikely to strongly compromise either the present values of ΣQ , or the comparative estimates for NGC 7027 or OMC-1, 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 H_I 20-5 through 22-5 is likely to be negligible). There are other indicators that extinction towards the central IR source is reasonably high. C¹⁸O mapping by Schwartz et al. (1983) indicates a local hydrogen column density

$N(\text{H}_2) \sim 4 \cdot 10^{21} \text{ cm}^{-2}$, implying $A_v \sim 4 \text{ mag}$, although the peak in $N(\text{H}_2)$ ($\sim 6 \cdot 10^{21} \text{ cm}^{-2}$) occurs approximately 2' to the northeast of this source. This rather low value for A_v 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 $A_v \sim 11 \text{ mag}$ (for $A_v/\tau_{10\mu\text{m}} \sim 12$, 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 $\geq 10^2 R_*$ (where R_* is the stellar radius), given an inner grain temperature $T_{gr} \sim 10^3 \text{ K}$. The corresponding $1 \mu\text{m}$ extinction would then range between $\tau \sim 20$ and $\tau \sim 70$ 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

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

which would be quite at variance with a simple shock excitation mechanism. Our own calculations show that Γ varies from 5.8 through to 2.8 for values of T_{ex} ranging from 10^3 K to $3 \cdot 10^3 \text{ K}$, and similar values are also predicted by the various shock models; from Kwan (1977) we determine $\Gamma \sim 2.8$. The Q -branch profile appears rather anomalous, therefore, and it would be interesting to seek 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 [$M_s \sim 1-2.5 M_\odot$; 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 Calvert and Cohen (1978) adduce $L_* \geq 844 (D/\text{kpc})^2 L_\odot$, and a spectral type of (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 Calvert and Cohen (1978) found a central extinction $A_v \sim 5.35 (\pm 0.3) \text{ mag}$, significantly higher than in the wings ($A_v \sim 2.7 \text{ mag}$), 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

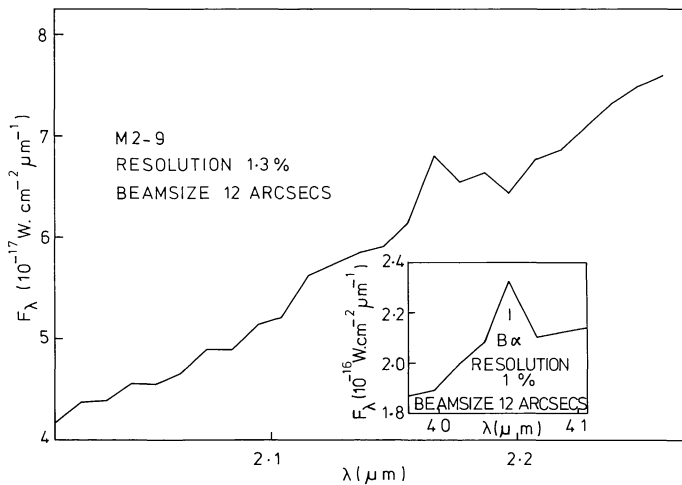


Fig. 4. As for Fig. 3, but with dust continuum subtracted. Note the strong $H_2V = 1-0S(1)$ emission, and the 7-10 transition of $He II$ blended with $Br\gamma$

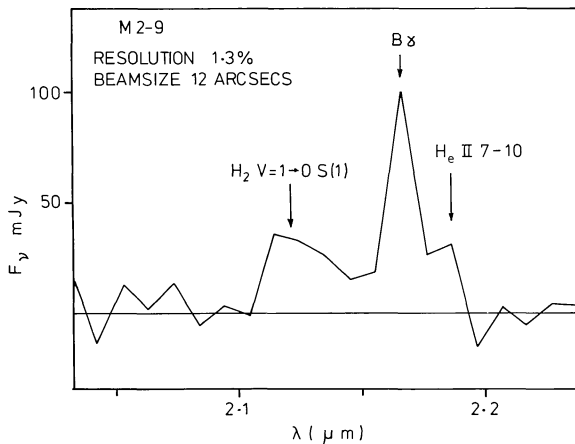


Fig. 4. As for Fig. 3, but with dust continuum subtracted. Note the strong $H_2V = 1-0S(1)$ emission, and the 7-10 transition of $He II$ blended with $Br\gamma$

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 α and γ hydrogen Brackett lines, the $v = 1-0S(1)$ transition of molecular hydrogen, and (blended with $Br\gamma$) the high excitation 7-10 transition of $He II$. 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 ~ 0.1 in diameter; a factor ~ 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 nebulosity. 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 $\nu \leq 14.7\text{ GHz}$. If a core-halo analysis similar to that of Olmon (1975) and Panagia and Felli (1975) is adopted, in which density varies with radius r as

$$n_e(r) = n_0, \quad r \leq R_c, \quad (5a)$$

$$n_e(r) = n_0 \left[\frac{r}{R_c} \right]^{-\beta}, \quad r > R_c, \quad (5b)$$

then the relatively shallow spectral index $\alpha = 0.5 \pm 0.28$ would imply a corresponding $\beta = 1.9_{-0.22}^{+0.32}$ (for both spherically symmetric and biconical halo structures). The turn-over frequency ν_c and flux S_{ν_c} for such a scenario are given through

$$\log S_{\nu_c} = 4.486 + \log \left[\frac{T_e^2}{D^2} 2nR_c^2 \nu_c^2 \right], \quad (6a)$$

$$\log \nu_c = -0.516 + \frac{1}{2.1} \log \left[\frac{8}{3} T_e^{-1.35} n_0^2 R_c \right], \quad (6b)$$

where ν_c is in GHz, S_{ν_c} in Janskies, T_e is the electron temperature, and R_c and D are in parsecs. Taking the observed flux at 14.7 GHz (Milne and Aller, 1982) to represent a lower limit to S_{ν_c} , we then find values $E = 2n_0^2 R_c > 6.4 \cdot 10^8\text{ cm}^{-6}\text{ pc}$, and a projected angular radius $\theta_c < 0.08$ for the core. From these relations it also follows that $7.7 \cdot 10^{-4} \geq 2R_c \geq 6.4 \cdot 10^8/n_0^2\text{ pc}$ for $D = 1\text{ kpc}$, whence $n_0 \geq 9.1 \cdot 10^5\text{ cm}^{-3}$. Note that although the model used here may not have *detailed* applicability to M2-9, the limits on θ and E are reasonably secure.

A corresponding analysis for the type I bipolars NGC 6537 and NGC 6302 leads to respective core size estimates of $2\theta_c \sim 0.8$ and 2.3 ; again very much smaller than the full extent of optical nebulosity, 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 adduced 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 α to Brackett γ (allowing for $A_v = 5.3\text{ mag}$ of central extinction) is found from our present results to be ~ 3.4 ;

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

Given that the Brackett γ flux is given through

$$F(\text{Br}\gamma) = 6.6 \cdot 10^{-27} [j_{\text{Br}\gamma}/j_{\text{H}\epsilon}] [j_{\text{H}\epsilon}/j_{\text{H}\beta}] E \sigma_s \text{ erg cm}^{-2} \text{ s}^{-1} \quad (7)$$

for an optically thin sphere very much smaller than the beam, subtending a solid angle σ_s , then we obtain a radius $\theta_c \sim 0.041$, and an emission measure $E \sim 4 \cdot 10^{10} \text{ cm}^{-6} \text{ pc}$ for $D \sim 1 \text{ kpc}$, and $n_e \sim 10^7 \text{ cm}^{-3}$.

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 $\Omega \sim 1.9 \cdot 10^{-9} \text{ rad s}^{-1}$, and assuming rotational equilibrium of the inner core and a stellar mass $\sim 2.5 M_\odot$ [characteristic of type I sources (Renzini and Voli, 1981)], then the angular radius of the rotating envelope must be ~ 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 $\sim 15''$ from the central star. This appears to be implausible on dynamical grounds, however. If for instance we assume the ad hoc, and exceptionally low distance of $\sim 50 \text{ pc}$ promoted by these authors, a total mass of $\sim 2.7 \cdot 10^4 M_\odot$ 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 $\sim 10^4$.

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 ~ 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 $L_* > 844 (D/\text{kpc})^2 L_\odot$, and a spectral class of (at minimum) B1V. The total Lyman continuum photon flux for such a star would be $\sim 3.3 \cdot 10^{45} \text{ s}^{-1}$ (Panagia, 1973), which would in turn lead to a Stromgren sphere with $n_e^{2/3} R \sim 4.4 \text{ cm}^{-2} \text{ pc}$. Given again that $n_e \sim 10^7 \text{ cm}^{-3}$, then we obtain $\theta \sim 0.02 \text{ arcsecs}$ and $E \sim 1.9 \cdot 10^{10} \text{ cm}^{-6} \text{ pc}$.

This radius, whilst confirming the small central core size, is nevertheless significantly smaller than found from the $\text{Br}\gamma$ 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 ($\sim \text{B0.5V}$) 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% neblosity) and excesses at 1.65 μm are taken to arise from grains with temperature $\sim 1300 \text{ K}$ (close to silicate sublimation temperatures), then for grains with radius $a \sim 10^{-5} \mu\text{m}$, mean Planck volume emissivity $\bar{\epsilon}(T_{gr}, a)$, and U.V. absorptivity $\bar{Q}_{\text{U.V.}} = 1$, the inner radius of the dust shell occurs at

$$R_I \simeq \left[\frac{3L_*}{64\pi a \bar{\epsilon} \sigma T_{gr}^4} \right]^{1/2} \quad (8)$$

If, following Aitken and Roche (1982), we further presume a silicate grain composition (i.e., $\bar{\epsilon} \sim 10^3$; Gilman, 1974), then for a B0.5V irradiating star we derive $\theta_I \simeq 0.056 (D/\text{kpc})^{-1}$. On this basis, the bulk of short wave ($\lambda \leq 3.6 \mu\text{m}$) emission would be expected to arise from an extremely small central region, and this is indeed observed; Allen and Swings (1972) find 2 μm emission to predominantly derive from the central $\sim 12\%$ volume of the 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 ~ 1.5 of $R_c = 0.05$, 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% which, although its nature is not entirely clear, is in all probability neutral. The U.V. extinction through this zone must be of order $\sim 11 \text{ mag}$ at $\lambda \sim 0.1 \mu\text{m}$, 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 α optical depth $\tau(\text{H}\alpha) \sim 1.4 \cdot 10^{-30} n_e^2 R_c \sim 75$ (Kaplan and Pikelner, 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 $\text{H}\alpha/\text{H}\beta$ and $\text{H}\beta/\text{H}\gamma$ are also consistent with a value $\tau(\text{Ly}\alpha) \sim 10^4$ 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 $\sim 10\%$ 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 He II 7–10 transition at $\lambda \sim 2.19 \mu\text{m}$ appears to be relatively strong, although blended at

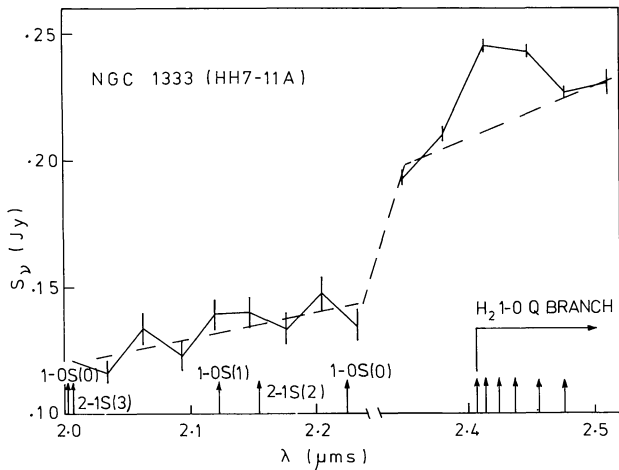


Fig. 5. Near-infrared spectrum for NGC 1333 (HH7-11A). The Q branch emission is seen to be superimposed upon a strongly rising dust continuum, although there is no corresponding evidence for S branch emission

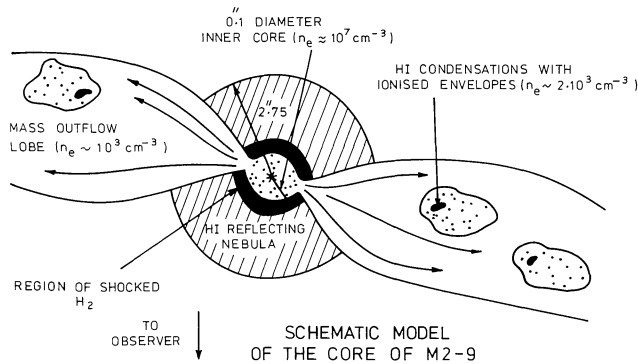


Fig. 6. Schematic representation (not to scale) of the M2-9 core zone. The outflow wind interacts with (and accelerates) neutral condensations in the lobes, whilst the primary H₂ emission is confined to an extremely small core shock zone

these resolutions with B_{ν} . The prevalence of both H₂S(1) and HeII 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 HI masses, and substantial stellar winds. Rather more extraordinary is the complete absence of enhanced HeI 2'S–2'P at $\lambda \approx 2.06 \mu\text{m}$. 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 Ly α optical depth (Thompson and Tokunaga, 1980).

The overall picture emerging from this work is illustrated in Fig. 6. Given a normal value of $A_{\nu}/(N(\text{H}_2) + 0.5N(\text{H})) \sim 10^{-21} \text{ mag cm}^2$, the central 5/5 collimating zone would then have a mass $\sim 0.1 M_{\odot}$, and the 0.1 core ionised mass would be $\sim 1.5 \cdot 10^{-5} M_{\odot}$; values not unreasonable for a protoplanetary nebula, but appreciably smaller than might have been expected for a type I object ($1\text{--}2.5 M_{\odot}$; Renzini and Voli, 1981). Given a mean lobe density $\bar{n}_e \sim 2 \cdot 10^3 \text{ cm}^{-3}$ (Walsh, 1981) we also estimate an ionised mass $\sim 1.7 \cdot 10^{-3} M_{\odot}$ for the wings alone. The extinction in the lobes for a normal value of $A_{\nu}/N(\text{H})$ would then be $A_{\nu} \sim 0.1 \text{ mag}$; 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 ($\sim 1 \text{ kpc}$) assumed here.

Note, however, that there is some evidence in other planetaries for depressed values of $A_{\nu}/(N(\text{H}_2) + 0.5N(\text{H}))$ 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 HI and HII zones – that is, in a very small central volume of inner radius ~ 0.05 – then we obtain an S(1) radiative rate $\sim 6.0 \text{ erg cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$. The rate of heat input into the shock for a pre-shock density n_0 , and shock velocity V_s is given by $n_0 V_s (\frac{1}{2} M_{\text{H}_2} V_s^2)$. If this now equated with the S(1) radiative rate quoted above (a severe lower limit to the total cooling), then we obtain $n_0 \gtrsim 6.7 \cdot 10^6 \text{ cm}^{-3}$ for $V_s \approx 15 \text{ km s}^{-1}$; 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 $n_0 \gtrsim 2 \cdot 10^8 \text{ cm}^{-3}$. Such a large (and probably unrealistic) value for n_0 argues in turn for significantly lower values of V_s (and this is also required on dynamical grounds; see later). For $V_s \sim 2 \text{ km s}^{-1}$, for instance, the requisite n_0 would be reduced by \sim 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 a hypothesis for M2-9. In the first place, the S(1) $V=2-1$ line at $\lambda = 2.248 \mu\text{m}$ would be expected to be relatively strong for such a mechanism, of order $\sim 0.55 S(1) V=1-0$, which would not be the case for collisional enhancement (Black and Dalgarno, 1976; Black et al., 1981). We observe a 2σ upper limit $S(1) V=2-1/S(1) V=1-0 \leq 0.26$. 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 10^5 K radiation field with dilution $1.2 \cdot 10^{-14}$. Scaling this model to M2-9, we find that a B0.5V star with $L \sim 2 \cdot 10^4 L_{\odot}$ 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 $L \sim 2 \cdot 10^7 L_{\odot}$. 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 $\lambda \sim 2.035 \mu\text{m}$, 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 10^5 K radiation field) predominate, imply a ratio $V=1-0S(2)/V=1-0S(1) \approx 0.42$. This is barely different from the predictions of a shock model [Hollenback and Shull (1977) suggest $S(2)/S(1) \approx 0.27$ to 0.39 for a velocity range $V_s \approx 6\text{--}14 \text{ km s}^{-1}$], and given that at least two of the nebulae considered by Isaacman have Zanstra temperatures comparable to or greater than $\sim 10^5 \text{ K}$, the detection of $S(2) V=1-0$ 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 $V = 1 - 0S(2)$ intensity.

4.3. CO observations of the central core

Given that the central dust may have a temperature as high as ~ 400 K, based on the colour temperature of the $10\ \mu\text{m}$ 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 $T_R^* \sim 4$ 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 emission is present at the source radial velocity above a 2σ limit of ~ 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

$$\tau_{J-J+1} = \frac{3.45 \cdot 10^{-15} (J+1) e^{-\frac{5.54(J+1)J}{2T_{ex}}} \left[1 - e^{-\frac{5.54(J+1)}{T_{ex}}} \right] N(^{12}\text{CO})}{\Delta V T_{ex}} \quad (9)$$

for a large velocity gradient (LVG) model in which $N(^{12}\text{CO})$ is the CO column density, then if a more conservative CO excitation temperature $T_{ex} \sim 100$ K is adopted [based on FIRIRAS photometry for other planetaries; Pottasch (1983)], we obtain a velocity range through the $5''.5$ core of $\Delta V \lesssim 12\ \text{km s}^{-1}$ (where we again assume a central $A_v \sim 2.6$ mag, and adopt $A_v/N(\text{H}_2) \sim 10^{-21}$ mag cm², $N(\text{CO})/N(\text{H}_2) \sim 10^{-4}$). This implies a plausible expansion timescale $\tau_{exp} \lesssim 2 \cdot 10^3$ yr.

It is interesting in this context to note that Walsh (1981) finds splitting of the central H α line which would suggest expansion at velocity $\sim 30\ \text{km s}^{-1}$. Given the small size of central core, the expansion timescale then becomes inordinately short, of order ~ 8 yr. It is likely therefore that the observed H α 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 $\sim r^{-2}$, from an initial value $\sim 10^7\ \text{cm}^{-3}$, to the typical densities $\sim 10^3\ \text{cm}^{-3}$ observed by Walsh (1981) outside of the main condensations ($\sim 10''$ from the core). The central (ionised) core itself must clearly be expanding rather slowly (at no more than ~ 0.1 – $1\ \text{km s}^{-1}$, 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_s sweeps up a neutral envelope of mass

$$M_s = M_0 \left[\frac{R_s}{R_0} \right]^\beta, \quad (10)$$

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

$$R_s^\beta V_s \frac{dV_s}{dR_s} + \beta R^{\beta-1} V_s^2 = \frac{V_w}{M_0} R_0^\beta \frac{dM_w}{dt} \quad (11)$$

for which the simplest analytical solution with varying M_s is given by $\beta = 1$. This yields $V_s^2 \approx (V_w R_0 dM/dt)/M_0$ for $R_s \gg R_I V_w$, where R_I is the initial radius of expansion, and for $V_s \sim 1\ \text{km s}^{-1}$, $dM_w/dt \sim 10^{-7} M_\odot \text{ yr}^{-1}$, $R_s = R_I = 7.5 \cdot 10^{14}$ cm, and $V_w \sim 250\ \text{km s}^{-1}$, we then find $M_s/M_\odot \sim 6 \cdot 10^{-3}$, and an expansion period $\approx 2.5 \cdot 10^2$ yr.

Whilst the model above has a purely pedagogical value, it is clear that a relatively modest size for the ionised core does not

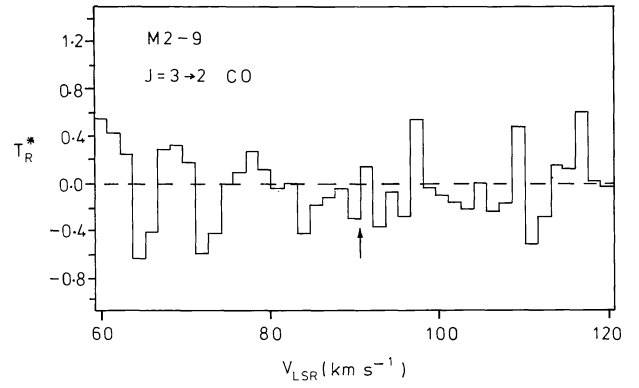


Fig. 7. $J = 3 - 2$ CO spectrum towards M2-9, in which the respective source V_{LSR} is indicated by an arrow

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 H₂ 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 H₂, ranging from $M(\text{H}_2) < 10^{-10} M_\odot$ for As 353, to a few times $10^{-5} M_\odot$ for V645 Cygni. Between $2.5 \cdot 10^{-4}$ and $1.9 \cdot 10^{-5} M_\odot$ of H₂ appears to be present in NGC 1333 (given $10^3\ \text{K} \leq T_{ex} \leq 2 \cdot 10^3\ \text{K}$), 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 $dM/dt \sim 2 \cdot 10^{-7} M_\odot \text{ yr}^{-1}$, and $V_w \sim 10^3\ \text{km s}^{-1}$; parameters typical of other, similar sources. The mass of H₂ in M2-9 lies probably between $4.2 \cdot 10^{-8} M_\odot$ and $1.4 \cdot 10^{-6} M_\odot$, estimated for the $V = 1 - 0S(1)$ line, and appreciable He II $\lambda = 2.19\ \mu\text{m}$ 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 H₂ emission rate and low pre-shock velocity; a U.V. cascade model can probably be discarded for this source. No $J = 3 - 2$ CO emission 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 $A_v/N(\text{H}_2)$, and an expansion timescale $\tau_{exp} \lesssim 2 \cdot 10^3$ yr. The levels of extinction derived from the higher order members of the Balmer series are broadly confirmed by the B γ and B α line measures, which may in turn indicate masses $M_N \sim 0.1 (10^{-21} [N(\text{H}_2) + 0.5N(\text{H})]/A_v) M_\odot$ 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.

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