Near-infrared, IFU spectroscopy unravels the bow-shock HH99B^{★,★★}

T. Giannini¹, L. Calzoletti^{1,2}, B. Nisini¹, C. J. Davis³, J. Eislöffel⁴, and M. D. Smith⁵

¹ INAF – Osservatorio Astronomico di Roma, via Frascati 33, 00040 Monte Porzio Catone, Italy
 e-mail: [giannini;nisini;calzol]@oa-roma.inaf.it

² Università di Cagliari, via Università 40, 09124 Cagliari, Italy

³ Joint Astronomy Centre, 660 North A'ohōkū Place, University Park, Hilo, HI 96720, USA
 e-mail: c.davis@jach.hawaii.edu

⁴ Thüringer Landessternwarte, Sternwarte 5, 07778 Tautenburg, Germany
 e-mail: jochen@tls-tautenburg.de

⁵ Centre for Astrophysics & Planetary Science, School of Physical Sciences, The University of Kent, Canterbury CT2 7NR, UK
 e-mail: m.d.smith@kent.ac.uk

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ABSTRACT

Aims. We aim at characterising the morphology and the physical parameters governing the shock physics of the Herbig-Haro object HH99B. We obtained SINFONI-SPIFFI IFU spectroscopy ($R \sim 2000\text{--}4000$) between 1.10 and $2.45\ \mu\text{m}$ detecting more than 170 emission lines, that, to a large extent, have never observed before in a Herbig-Haro object. Most of them come from ro-vibrational transitions of molecular hydrogen ($v_{\text{up}} \leq 7$, $E_{\text{up}} \lesssim 38\,000\ \text{K}$) and [Fe II] ($E_{\text{up}} \lesssim 30\,000\ \text{K}$). In addition, we observed several hydrogen and helium recombination lines, along with fine-structure lines of ionic species. All the brightest lines appear resolved in velocity.

Methods. Intensity ratios of ionic lines were compared with predictions of NLTE models to derive bi-dimensional maps of extinction and electron density, along with estimates of temperature, fractional ionisation, and atomic hydrogen post-shock density. The H_2 line intensities were interpreted in the framework of Boltzmann diagrams, from which we have derived extinction and temperature maps of the molecular gas. From the intensity maps of bright lines (i.e. $\text{H}_2\ 2.122\ \mu\text{m}$ and [Fe II] $1.644\ \mu\text{m}$), the kinematical properties of the shock(s) at work in the region were delineated. Finally, from selected [Fe II] lines, constraints on the spontaneous emission coefficients of the 1.257 , 1.321 , and $1.644\ \mu\text{m}$ lines are provided.

Results. Visual extinction variations up to 4 mag emerge, showing that the usual assumption of constant extinction could be critical. The highest A_V is found at the bowhead ($A_V \sim 4$ mag) while diminishing along the flanks. The electron density increases from $\sim 3 \times 10^3\ \text{cm}^{-3}$ in the receding parts of the shock to $\sim 6 \times 10^3\ \text{cm}^{-3}$ in the apex, where we estimate a temperature of $\sim 16\,000\ \text{K}$ from [Fe II] line ratios. Molecular gas temperature is lower in the bow flanks ($T \sim 3000\ \text{K}$), then progressively increases toward the head up to $T \sim 6000\ \text{K}$. In the same zone, we are able to derive the iron gas-phase abundance ($\sim 60\%$ of the solar value) from the [Fe II] 1.257 /[P II] 1.187 line ratio, along with the hydrogen fractional ionisation (up to 50% at the bowhead) and the atomic hydrogen post-shock gas density ($\sim 1 \times 10^4\ \text{cm}^{-3}$). The kinematical properties derived for the molecular gas substantially confirm earlier ones, while new information (e.g. $v_{\text{shock}} \sim 115\ \text{km s}^{-1}$) is provided for the shock component responsible for the ionic emission. We also provide an indirect measure of the H_2 breakdown speed (between 70 and $90\ \text{km s}^{-1}$) and compute the inclination angle with respect to the line of sight. The map parameters, along with images of the observed line intensities, will be used to put stringent constraints on up-to-date shock models.

Key words. stars: circumstellar matter – infrared: ISM – ISM: Herbig-Haro objects – ISM: individual objects: HH99 – ISM: jets and outflows

1. Introduction

Mass loss phenomena in the form of powerful bipolar jets and molecular outflows are often associated with the early evolution of protostars. Along with indirectly regulating the accretion process, they play a crucial rôle in the interaction between the protostar and the natal environment, causing injection of momentum, kinetic energy, and turbulence in the ISM, as well as

irreversible modifications of its chemical structure and physical conditions. The most violent interaction occurs at the terminal working surface, where the supersonic flow impacts the undisturbed medium and most of the ambient material is entrained by the jet (e.g. Reipurth & Bally 2001). In a schematic model, the interaction occurs via two shocks: an internal working surface (Mach disk) that decelerates the jet gas and a forward shock that accelerates the ambient gas, producing a mixture of shock velocities (e.g. Hartigan 1989). The latter often has a curve-shaped morphology, therefore, only the component of motion along the jet axis is slowed going from the apex of the shock toward the receding parts, where large transverse motions occur. In a classical scenario for sufficiently fast shocks, the head of the bow is

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** Line images listed in Tables 1 and 2 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/481/123>

a purely dissociative (J)ump-type shock (Hollenbach & McKee 1989), which changes along the bow flanks, where the impact occurs obliquely, to slower, non-dissociative (C)ontinuous-type shocks (Draine 1980). In this framework, highly excited ionic emission should arise at the head of the bow, while molecular emission mainly originates from the cooling regions along the flanks and behind the bow. Recent models, however, predict that mixtures of J- and C-type shocks can occur along the overall structure of the bow or, in the presence of a sufficiently strong magnetic field, that a J-type shock can evolve into a C-type, remaining embedded at an early time (Smith & Rosen 2003; Smith & Mac Low 1997; Flower et al. 2003; Le Boulrot et al. 2002; Lesaffre et al. 2004a,b).

The large number of parameters that regulate the shock physics (e.g. strength and direction of the local magnetic field, ionisation fraction, and density gradient between the shocked gas and the local environment) can only be constrained through dedicated observations aimed at probing the physical and kinematical properties of the gas along the whole bow structure. In this respect, observations in the near-infrared represent as appropriate tool: both H_2 ro-vibrational lines, which are the main gas coolants in continuous shock components, and fine structure transitions of abundant atomic species (e.g. Fe II, C I, S II), which are expected to emit in dissociative shocks, fall in this wavelength range. Indeed, in recent years multiple observations of jets and bow shocks have been conducted in the near-infrared by means of long-slit spectroscopy (e.g. Eislöffel et al. 2000; Giannini et al. 2004; Smith et al. 2003; Nisini et al. 2002; O’Connell et al. 2004; Nisini et al. 2005). The observed spectra are typically rich in both molecular (H_2) and ionic ([FeII]) lines, implying that strong gradients in the local conditions (e.g. temperature, fractional ionisation) do occur and that multiple shock components are simultaneously at work.

The main limitation of long-slit spectroscopy for studying bow-shock morphologies in detail arises from the poor coverage of the extended bow surface usually obtainable in a reasonable amount of observing time. In contrast, Integral Field Spectroscopy (IFU) represents a well-tailored tool for overcoming this problem, since it allows us to obtain 2-D maps simultaneously at different wavelengths. In this paper we present the spectral images obtained with the IFU facility SINFONI (Eisenhauer et al. 2003; Bonnet et al. 2004) of a prototype bow-shock, namely the Herbig-Haro object HH99B. This is located in the RCrA molecular core at $d \sim 130$ pc (Marraco & Rydgren 1981), and it was first discovered in the optical by Hartigan & Graham (1987), who suggested it is the red-shifted lobe of the outflow powered by the HH100-IR source. More recently, Wilking et al. (1997) have proposed, on the basis of near-infrared images, the infrared source IRS9 and the Herbig Ae star RCrA as other possible exciting source candidates. HH99B was first imaged in the near-infrared by Davis et al. (1999, hereafter D99) who identified three different emission zones: one at the head of the bow (subsequently named B0 by M’Coe et al. 2004, hereafter MC04) where the bulk of the emission comes from ionised gas, and two bow flanks (knots B1 and B3), which mainly emit in H_2 lines. Another H_2 knot, immediately behind the bow apex, was identified as knot B2. In the framework of both bow- (D99) and planar- (MC04) shock models, some attempt has been made to model the line emission observed in HH99B: the H_2 morphology is well-fitted by a C-type bow shock, while the physical conditions of the molecular gas (measured by means of long-slit spectroscopy) have been accounted for by a planar J-type shock with a magnetic precursor. None of these two models, however,

is able to reproduce the copious ionic emission, which requires the presence of a further fully dissociative shock component.

With the present work we aim at putting strong observational constraints on bow-shock models (whose detailed application will be the subject of a later paper). In particular we intend to (i) morphologically characterise the emission of the different lines; (ii) derive maps of the main physical parameters that govern the shock physics; and (iii) study the velocity field(s) along the bow structure.

Our work is organised as follows. Section 2 describes our observations and results; the line excitation analysis and the kinematical properties are then presented in Sects. 3 and 4. Concluding remarks are given in Sect. 5, while in Appendix A we describe the procedure we have applied to deriving the inclination angle of HH99B.

2. Observations and results

HH99B was observed during four different runs in May and July 2006 with the SINFONI-SPIFFI instrument at the VLT-UT4 (ESO Paranal, Chile). The coordinates of the pointed position are $\alpha_{2000} = 19^h02^m05.4^s$, $\delta_{2000} = -36^\circ54'39''$. The Integral Field Unit was employed to obtain spectroscopic data in J (1.10–1.40 μm), H (1.45–1.85 μm) and K (1.95–2.45 μm) bands, at spectral resolutions 2000, 3000, and 4000, respectively, each wavelength band fitting on the 2048 pixels of the Hawaii detector in the dispersion direction. An image slicer converts the bidimensional field-of-view into a one-dimensional long-slit, which is fed into a spectrograph to disperse the light of each pixel simultaneously. As a consequence, seeing and atmospheric response can affect neither the emission morphology at a given wavelength nor intensity ratios of lines within the same filter. The spatial resolution was selected at 0.25'' per image slice, which corresponds to a field-of-view of $8'' \times 8''$. No adaptive optics is supported in this configuration. The total integration time is 2400 s, 1500 s, and 1800 s in the J , H , and K bands, respectively.

The observations were acquired by nodding the telescope in the usual ABB’A’ mode and a telluric B-type standard star close to the source was observed to remove the atmospheric spectral response.

The SINFONI data-reduction pipeline (Modigliani et al. 2007) was used to subtract the sky emission, to construct dark and bad pixel maps and flat field images, to correct for optical distortions, and to measure wavelength calibration by means of Xenon-Argon lamp images. Further analysis was carried out with IRAF packages and IDL scripts, which were used to remove telluric absorption features. This task was accomplished by dividing the target images by those of the telluric standard star, once corrected for both the stellar continuum shape (a black-body function at the stellar temperature) and its intrinsic absorption features (mainly hydrogen recombination lines). Photometric calibration was obtained from the same standard star. Since there is no overlapping in the spectral range covered by the different grisms, no cross-calibration was performed at this step of the data reduction. However, we checked the reliability of our absolute fluxes a posteriori once an extinction map for the H_2 line emission was obtained (Sect. 3.1.2). We measured the departure from the theoretical value in the image ratio of dereddened lines coming from the same level and lying in different spectral bands. In this way we estimated a cross-calibration better than 5% between the J and H bands and better than 12% between the H and K bands. Atmospheric OH lines were also

used to refine wavelength calibration and to measure the effective spectral resolution: we obtained $R \sim 1900, 2700, 3500$ in J , H , and K bands, that correspond to 160, 110, 85 km s⁻¹, respectively. At these spectral resolutions we were able to resolve the brightest lines (e.g. H₂ 2.122 μ m and [Fe II] 1.644 μ m), which are observed at S/N ratios of $\sim 10^2$ – 10^3 . As a final step, images of lines observed in individual bands ([Fe II] 1.257 μ m and 1.644 μ m in the J and H bands and H₂ 2.122 μ m in the K band) were used to re-align the images acquired in different observing runs.

As a result, we obtained a 3D data-cube containing the HH99B image in more than 170 lines. As an example of our results, we integrated the signal in the areas corresponding to knots B0 and B3 (see Fig. 1): the corresponding spectra are shown in Figs. 2–4. The large majority of the detected lines are H₂ ro-vibrational lines (121). For these, we list in Table 1 spectral identification, vacuum wavelength, excitation energy (in K), and the maximum S/N ratio registered in the corresponding image. The detected ro-vibrational transitions come from levels with $v \leq 7$ and E_{up} up to $\sim 38\,000$ K, many of them never before observed in HH objects. In particular, as we show in Fig. 1 (upper panel), emission of lines with $E_{\text{up}} \lesssim 30\,000$ K is present only along the bow flanks, while lines with $E_{\text{up}} \gtrsim 30\,000$ K are observed in the whole shock, peaking at the bow head. Therefore, two main results emerge: (i) molecular hydrogen also survives where ionic emission is strong (see below); and (ii) temperature gradients do exist along the shock, with the highest values reached at the bow head, where stronger excitation conditions are expected to occur.

Atomic lines are listed in Table 2 and some examples of the observations are shown in the middle and bottom panels of Fig. 1. Plenty of [Fe II] lines are detected (34 lines), emitted from levels with $E_{\text{up}} \lesssim 30\,000$ K. As for H₂, two groups of lines are identified: those with $E_{\text{up}} \lesssim 13\,000$ K, which come for the a⁴D level, are observed in the whole region, while those at higher excitation energy are only emitted at the bow head. In this same area, emission of hydrogen and helium recombination lines (8 and 3 lines, respectively, see Fig. 1, bottom panel) along with fine-structure lines of [P II], [Co II], and [Ti II] are detected. Other fine structure lines commonly observed in Herbig-Haro objects (e.g. [C I] at 0.98 μ m, [N I] at 1.04 μ m, [S II] at 1.03 μ m, Nisini et al. 2002) are not covered with SINFONI. In fact, the first wavelength in the J band is $\lambda = 1.10 \mu\text{m}$, i.e. longer than that of other infrared spectrographs (e.g. ISAAC and SofI at ESO are able to observe wavelengths longer than 0.98 μ m and 0.86 μ m, respectively).

To check for possible line variability, the intensities of atomic and molecular lines observed with SINFONI were compared with the ones observed by MC04 in July 2002 (i.e. four years before our SINFONI observations). Synthetic slits corresponding to slits 1 and 2 of MC04 (PA = 32.4° and 329.5°, width 0.6'') were superimposed onto the SINFONI images and the flux integrated over the same regions as in that paper. The main difference between SINFONI and ISAAC spectra is represented by the significantly larger number of lines observed with SINFONI (see Figs. 2–4 and Fig. 3 and Table 1 of MC04). In particular, many lines at high excitation were detected, both atomic and molecular, which indicate excitation conditions stronger than those inferred in that paper (see Table 3). A general increase in the intensities of lines observed with both the instruments is registered, but with differential behaviour among molecular and ionic lines, which are respectively 4 and 1.5 times brighter than four years earlier. Such variability has been observed in proper motion studies, over time periods of

a few years, which are typical of radiative cooling times in HH objects (e.g. Caratti o Garatti et al. 2008).

3. Diagnostics of physical parameters

The most prominent features observed in HH99B are the [Fe II], H₂, and H lines, and we therefore used these transitions to derive some physical parameters of the shock.

3.1. Fe analysis

3.1.1. The [Fe II] Einstein coefficients

In Table 2 the [Fe II] lines are listed by grouping transitions originating from the same upper level. The intensity ratio of pairs of (optically thin) lines in each group is independent of the local physical conditions, since they are only function of atomic parameters (i.e. line frequencies and Einstein A coefficients for spontaneous emission). Hence, the *observed* intensity ratios among these lines can be efficiently used to measure the local extinction (e.g. Gredel 1994). Unfortunately, the complexity of the energy level system of iron makes an accurate computation of the A values very difficult, so that three distinct sets of these parameters, differing by more than 30%, have so far been listed in the literature: two were computed with different methods by Quinet et al. (Q-SST, Q-HFR, 1996), and one provided by Nussbaumer & Storey (NS, 1988). A fourth list, based on the observation of P Cygni, was recently published by Smith & Hartigan (SH, 2006), who find A values 10%–40% higher than theoretical computations. The application of one set rather than another can lead to significant differences in the derivation of the local extinction. For example, the NS coefficients of the 1.644 μ m and 1.257 μ m lines (both coming from the level a⁴D_{7/2} with $E_{\text{up}} = 11\,446$ K and more commonly observed) provide an extinction 2.7 mag higher than which is derivable from the Q-SST coefficients. This marginally affects the NIR lines (the intensity grows by a factor of 2.8 for a line at 1 μ m and a by factor of 1.4 for a line at 2 μ m), but becomes critical at optical wavelengths (the intensity grows by a factor of 33.6 at 0.5 μ m).

The large number of [Fe II] lines detected in HH99B, observed with a high S/N ratio in a remarkably large fraction of pixels, offers us the opportunity to compare theoretical predictions on the spontaneous emission rates with a significant sample of observational points. To this aim, we have plotted the ratios $I(1.257 \mu\text{m})/I(1.644 \mu\text{m})$ vs. $I(1.321 \mu\text{m})/I(1.644 \mu\text{m})$ in Fig. 5, since these are observed at very high S/N (higher than 100). In the same figure, green dashed curves represent the Rieke & Lebofsky (1985) extinction law¹ applied to the intrinsic ratios expected for the four sets of A coefficients (Q-SST, Q-HFR, NS, and SH). Squares along these “extinction curves” indicate $A_V = 0, 5, 10$ mag.

First of all, we note that all the HH99B data lie definitively to the right of any of the plotted extinction curves. Since different A_V can move the points only *along* extinction vectors, no theoretical intrinsic ratio is consistent with the observed points. This result has already been pointed out in Nisini et al. (2005), who discuss how the extinction along the knots of the HH1 jet determined from the 1.321 μ m/1.644 μ m ratio is always smaller than derived from the 1.257 μ m/1.644 μ m ratio, irrespective of

¹ The following arguments remain valid if other extinction laws are adopted (e.g. Cardelli et al. 1988), since these do not appreciably differ from the Rieke & Lebofsky law over the short wavelength range taken into consideration (from 1.257 μ m to 1.644 μ m).

Fig. 1. Selected spectral images from our HH99B data-cube. Intensities are given on a colour scale. Offsets are from $\alpha_{2000} = 19^{\text{h}}02^{\text{m}}05.4^{\text{s}}$, $\delta_{2000} = -36^{\circ}54'39''$. **A)** $H_2:1-0\ S(1)$ at $2.122\ \mu\text{m}$. The locations of the knots labelled by D99 (B_1 , B_2 and B_3) and MC04 (B_0) are indicated; **B)** $H_2:2-1\ S(17)$ at $1.758\ \mu\text{m}$; **C)** $[\text{Fe II}]: a^4D_{7/2}-a^4F_{9/2}$ at $1.644\ \mu\text{m}$. The black line defines the area where $[\text{Fe II}]$ lines at $S/N > 100$ are detected and used to construct the plot of Fig. 5; **D)** $[\text{Fe II}]: a^4P_{3/2}-a^4D_{7/2}$ at $1.749\ \mu\text{m}$; **E)** $\text{H}: \text{Pa}\beta$ at $1.282\ \mu\text{m}$; **F)** $[\text{P II}]: ^2D_2-^3P_2$ at $1.188\ \mu\text{m}$. White rectangles in panels **A)** and **C)** indicate the areas over which we have integrated the signal and extracted the spectra shown in Figs. 2–4.

the adopted theoretical set of A coefficients. The HH99B data are also inconsistent with the PCygni datum (green triangle in Fig. 5) and consequently with the A coefficients extrapolated from it.

To be confident about the reliability of our data, we checked for possible blendings of the $[\text{Fe II}]$ lines with other lines or telluric features. In this respect, the $1.644\ \mu\text{m}$ line is close to both the H_2 line $3-1\text{O}(7)$ at $1.6453\ \mu\text{m}$ (see Table 1 and Fig. 3) and a

Fig. 2. *J*-band spectrum extracted in knots B3 (black) and B0 (red), over an area of 0.5 and 1.25 arcsec², respectively.

telluric OH feature at $1.6442\ \mu\text{m}$ (Lidman & Cuby 2000). This one was removed in the sky subtraction procedure, and its residuals estimated to affect the $1.644\ \mu\text{m}$ flux by less than 0.5%. The H_2 line, coming from a low excitation level ($E_{\text{up}} \sim 19\,000\ \text{K}$), is observed only in the receding parts of the bow, hence is *spatially* separated from the $1.644\ \mu\text{m}$ emission region.

To check for other observational or data-reduction biases (e.g. unfavourable observational conditions, flat-fielding, inter-calibration of lines lying in different bands), we searched in the literature for other observations of the considered lines obtained with other instruments. To minimise the uncertainties, we considered only line ratios observed with $S/N \geq 30$, which are shown with different colours/symbols in Fig. 5. Notably, all of

them occupy the right side of the plot, in agreement with the HH99B points. This result, which reinforces the reliability of our observations, allows us to derive new A coefficients from our observations, provided that these are accurately corrected for the visual extinction value (measured independently from [Fe II] lines). In this respect, two facts have to be noted: (i) although the sky area considered for this analysis is a few arcsec² (marked in black in Fig. 1, middle left panel), an extinction gradient of ~ 1 mag occurs in this zone, as evidenced by the scatter among the data points of Fig. 5; (ii) in the same area, we were able to obtain just a gross estimate of A_V (1.8 ± 1.9 mag) from the observed Pa α /Br γ ratio (see Sect. 3.3). Both these circumstances prevent us from deriving an accurate measure of the

Fig. 3. As in Fig. 2 for the H band.

A ratios. A rough estimate can however be obtained by dereddening the average of the HH99B data (black cross) for $A_V = 1.8$ mag, which gives $A_{1.321}/A_{1.644} = 0.38$ and $A_{1.257}/A_{1.644} = 1.24$. The main uncertainty on these values comes from the A_V estimate, more than from the error on the line fluxes. Taking the A_V error of 1.9 mag into account, we can state that the theoretical points do belong to the segment of the extinction curve (along which they are constrained to move) starting at the point [0.33,1.02] ($A_V = 0$ mag) and ending at the point [0.44,1.48] ($A_V = 3.7$ mag).

In conclusion, from a purely observational point of view, we can summarise as follows: (i) all the theoretically derived A values fail to reproduce the majority of the observed line ratios, irrespective of the extinction values; (ii) the best “recipe”

for deriving a reliable extinction estimate from [Fe II] lines is (at least when only the three considered lines are detected) to use the NS coefficients for the $1.321\,\mu\text{m}/1.644\,\mu\text{m}$ ratio and the Q-HFR coefficients for the $1.257\,\mu\text{m}/1.644\,\mu\text{m}$ ratio, which are 8% and 5% lower than our determinations; (iii) dedicated observations of objects with well-known visual extinction should be performed to derive the [Fe II] Einstein A coefficients with sufficient accuracy.

3.1.2. Extinction map

Given the problems with the A coefficients outlined in the previous section, we applied the following procedure for constructing an extinction map across the HH99B bow from the

Fig. 4. As in Fig. 2 for the K band.

observed [Fe II] lines. To minimise the effect of the uncertainties, we used a number of line ratios involving bright lines from four energy levels (i.e. $a^4D_{7/2}$, $a^4D_{5/2}$, $a^4D_{3/2}$, $a^4P_{5/2}$) and at quite different wavelengths. With this set of ratios and by adopting the NS coefficients as a first attempt, we determined the extinction in a very small region at the bow head, where all the lines are detected with an S/N ratio higher than 30. This value was then used to calibrate the extinction map obtained from the $1.25 \mu\text{m}/1.644 \mu\text{m}$ ratio, which is the only one detected well above the noise level (at least at 5σ), even in the bow flanks. Contours of the final map are shown in Fig. 6: variations in A_V up to 4 mag are recognised in a total area of $\sim 10 \text{ arcsec}^2$. The highest A_V values (4–5 mag) are found at the bow head. If we

correct the observed [Fe II] lines for them, the emission peak (see Fig. 7) moves about 0.6 arcsec towards the northeast. Along the flanks, A_V is generally lower (up to 2–3 mag). Thus, the progressive fading in these zones of the Fe II emission cannot be ascribed to an increasing extinction, but rather reflects low excitation conditions and/or low abundance of the gas-phase iron.

As described above, the main uncertainty on the extinction map arises from the adopted set of the A values. We thus derived the same map from the $1.257 \mu\text{m}/1.644 \mu\text{m}$ ratio, now adopting our Einstein coefficients ratio of 1.24. We find that the largest difference between the two maps occurs at the emission peak, where it is ~ 0.6 mag. This implies a marginal increase in intrinsic line intensities (for example $I(1.644 \mu\text{m})$ increases by

Table 1. H₂ lines observed in HH99B.

H ₂ lines											
Line id.	λ_{vac} (μm)	E_{up} (K)	S/N_{max}^a	Line id.	λ_{vac} (μm)	E_{up} (K)	S/N_{max}	Line id.	λ_{vac} (μm)	E_{up} (K)	S/N_{max}
$v = 1$											
1–0S(0) ¹	2.2233	6471	44	1–0S(7)	1.7480	12 818	65	1–0S(21) ³	1.7195	38 136	7
1–0S(1)	2.1218	6951	650	1–0S(8)	1.7147	14 221	70	1–0S(23)	1.7801	42 122	4
1–0S(2)	2.0338	7584	48	1–0S(9)	1.6877	15 723	46	1–0Q(1)	2.4066	6149	44
1–0S(3)	1.9576	8365	46	1–0S(10)	1.6665	17 312	9	1–0Q(2)	2.4134	6471	30
1–0S(5) ²	1.8358	10 342	5	1–0S(18) ³	1.6586	32 136	3	1–0Q(3)	2.4237	6951	50
1–0S(6)	1.7879	11 522	30	1–0S(19) ³	1.6750	34 131	8	1–0Q(4)	2.4375	7584	18
$v = 2$											
2–0S(0)	1.1896	12 095	6	2–0Q(8)	1.3020	16 881	9	2–1S(1)	2.2477	12 551	44
2–0S(1)	1.1622	12 551	48	2–0Q(9) ⁵	1.3188	18 108	12	2–1S(2)	2.1542	13 151	22
2–0S(2)	1.1382	13 151	7	2–0Q(10)	1.3375	19 436	3	2–1S(3)	2.0735	13 891	40
2–0S(3)	1.1175	13 891	6	2–0Q(15)	1.4648	27 267	3	2–1S(4)	2.0041	14 764	21
2–0S(4)	1.0998	14 764	6	2–0Q(19) ³	1.6156	34 447	3	2–1S(5) ²	1.9448	15 764	30
2–0Q(1)	1.2383	11 790	14	2–0Q(2)	1.2932	11 636	7	2–1S(8) ⁶	1.8183	19 435	7
2–0Q(2) ⁴	1.2419	12 095	9	2–0Q(3)	1.3354	11 790	16	2–1S(9) ⁷	1.7904	20 855	22
2–0Q(3)	1.2473	12 551	22	2–0Q(6)	1.4870	13 151	5	2–1S(10)	1.7688	22 356	3
2–0Q(4)	1.2545	13 151	7	2–0Q(7)	1.5464	13 891	8	2–1S(13) ⁸	1.7364	27 267	6
2–0Q(5)	1.2636	13 891	11	2–0Q(9)	1.6796	15 764	5	2–1S(17) ³	1.7587	34 446	4
2–0Q(6)	1.2745	14 764	7	2–0Q(11)	1.8349	18 108	3	2–1S(18) ³	1.7753	36 301	3
2–0Q(7)	1.2873	15 764	9	2–1S(0)	2.3556	12 095	10	2–1S(19) ^{3,9}	1.7962	38 166	8
$v = 3$											
3–1S(0) ¹⁰	1.2621	17 388	9	3–1S(9)	1.1204	25 661	7	3–1O(5)	1.5220	17 819	10
3–1S(1)	1.2330	17 819	10	3–1Q(1)	1.3141	17 099	8	3–1O(7) ¹⁴	1.6453	19 087	9
3–1S(2)	1.2077	18 387	8	3–1Q(2) ¹²	1.3181	17 388	12	3–1O(9) ¹¹	1.7898	25 661	10
3–1S(3)	1.1857	19 087	9	3–1Q(3)	1.3240	17 819	8	3–2S(1)	2.3864	17 819	8
3–1S(4)	1.1672	19 913	8	3–1Q(5) ¹³	1.3420	19 087	9	3–2S(2)	2.2870	18 387	9
3–1S(5)	1.1520	20 857	10	3–1Q(11) ²	1.4479	25 661	8	3–2S(3)	2.2014	19 087	25
3–1S(6)	1.1397	21 912	5	3–1Q(13)	1.5024	28 558	6	3–2S(4)	2.1280	19 913	11
3–1S(7)	1.1304	23 071	7	3–1Q(15) ³	1.5685	31 691	6	3–2S(5)	2.0656	20 857	17
3–1S(8)	1.1241	24 323	5	3–1O(4)	1.4677	17 388	6	3–2S(7)	1.9692	23 071	14

10%) and does not critically affect the derivation of the physical parameters of the atomic gas (see next section).

3.1.3. Electron density map and temperature

To derive the electron density along the bow structure, we selected seven intensity ratios (i.e. $I_{1.533}/I_{1.644}$, $I_{1.600}/I_{1.644}$, $I_{1.677}/I_{1.644}$, $I_{1.664}/I_{1.644}$, $I_{1.271}/I_{1.257}$, $I_{1.279}/I_{1.257}$, $I_{1.328}/I_{1.257}$), involving lines close in wavelength (their differential extinction is negligible) and coming from levels with different critical densities (from $\sim 8 \times 10^2$ to $3 \times 10^5 \text{ cm}^{-3}$) and similar excitation energy ($E_{\text{up}} \sim 11\,000\text{--}12\,000 \text{ K}$), so that the dependence on the temperature is very weak. All these line ratios have been simultaneously fitted with a NLTE code that solves the equations of the statistical equilibrium for the first 16 fine-structure levels of [Fe II]. Spontaneous rates are taken from NS, while energy levels and rates for electron collisions are adopted from Pradhan & Zhang (1993). Assuming $T_e = 10\,000 \text{ K}$, we constructed the electron density map shown in Fig. 8; n_e is about $2\text{--}4 \times 10^3 \text{ cm}^{-3}$, with a peak up to $6 \times 10^3 \text{ cm}^{-3}$ at the bow head². These values are in the range commonly found in HH objects from embedded jets (e.g. Nisini et al. 2005; Podio et al. 2006).

In a restricted area at the bow head of about 1 arcsec² (see Fig. 1, middle right panel), we detected 13 lines at high

excitation (E_{up} between 20 000 and 30 000 K), which are suitable for evaluating the local electronic temperature. Of these, just four lines coming from the term a⁴P (i.e. 1.749 μm , 1.814 μm , 1.967 μm , 2.161 μm) can be modelled, since the collisional rates are unknown for the remaining nine lines.

To that aim, we enlarged our 16 level code by including another three fine-structure levels, for which the collisional coefficients are reported by Zhang & Pradhan (1995). Notably, the excitation energy of level #19 is around 32 000 K, well above the level #16 (less than 20 000 K); hence, the temperature range that can be probed with the 19 level code is sensitively enlarged. Having fixed extinction and electron density from the maps of Figs. 6 and 8, we fitted the de-reddened ratios with the 1.257 μm line, integrated over the area where the a⁴P lines are detected at $S/N \geq 5$. Results are plotted in Fig. 9, where the observed ratios are compared with the predictions of both the 16 and 19 level codes and for temperatures from 10 000 to 20 000 K. First, we note that, while at $T_e \lesssim 10\,000 \text{ K}$ the inclusion of three further levels does not change the results of the 16 level code, and strong differences emerge at higher temperatures (e.g. the ratio 1.257/1.749 decreases by about 70% at $T_e = 20\,000 \text{ K}$). Second, ratios with the 1.814 μm , 1.967 μm , and 2.161 μm lines agree well with $T_e \sim 16\,000\text{--}17\,000 \text{ K}$ (the latter line has been de-blended from the fundamental line of [Ti II], using an NLTE model for this species, Garcia-Lopez et al. 2008).

Finally, we note that the ratio with the 1.749 μm line implies $T_e \sim 8\,000 \text{ K}$, which we consider unreliable because in the same spatial region as examined here bright hydrogen and helium recombination lines are also observed (see Fig. 1). For this

² As we will see in the following, we estimate $T_e \sim 16\,000 \text{ K}$ in this part of the bow. At this temperature, the ratios involved in the electron density estimate can differ by less than 15% with respect to those computed at $T = 10\,000 \text{ K}$. This implies a very marginal increase in n_e .

Table 1. continued.

H ₂ lines											
Line id.	λ_{vac} (μm)	E_{up} (K)	S/N_{max}^a	Line id.	λ_{vac} (μm)	E_{up} (K)	S/N_{max}	Line id.	λ_{vac} (μm)	E_{up} (K)	S/N_{max}
$v = 4$											
4–2S(0) ¹⁵	1.3425	22 354	9	4–2S(8)	1.1987	28 885	7	4–2O(4) ¹⁸	1.5635	22 354	6
4–2S(1)	1.3116	22 760	14	4–2S(9)	1.1958	30 141	6	4–2O(5)	1.6223	22 760	7
4–2S(2)	1.2846	23 296	21	4–2Q(7)	1.4592	25 625	6	4–2O(6)	1.6865	23 297	4
4–2S(3) ¹⁶	1.2615	23 956	9	4–2Q(9)	1.4989	27 708	7	4–2O(7)	1.7563	23 956	7
4–2S(4) ¹⁷	1.2422	24 735	9	4–2Q(11) ³	1.5495	30 141	3	4–3S(3)	2.3445	23 956	6
4–2S(5)	1.2263	25 625	12	4–2Q(13) ³	1.6123	32 857	3	4–3S(4)	2.2667	24 735	3
4–2S(6)	1.2139	26 618	5	4–2Q(15) ³	1.6892	35 786	3				
4–2S(7)	1.2047	27 708	10	4–2O(3)	1.5099	22 081	6				
$v = 5$											
5–3S(3)	1.3472	28 500	4	5–3Q(1)	1.4929	26 737	3	5–3Q(7) ^{3,19}	1.5626	30 065	6
5–3S(4)	1.3270	29 231	3	5–3Q(2)	1.4980	26 994	9	5–3Q(11) ³	1.6673	34 291	4
5–3S(5) ³	1.3107	30 066	10	5–3Q(4)	1.5158	27 880	5	5–3Q(12) ³	1.7021	35 529	4
5–3S(7) ³	1.2894	32 017	7	5–3Q(6)	1.5443	29 230	3	5–3Q(13) ³	1.7412	36 821	5
$v = 6$											
6–4S(1) ³	1.5015	31 664	5	6–4Q(7) ³	1.6829	34 175	5	6–4O(4) ^{3,21}	1.7965	31 306	8
6–4Q(3) ³	1.6162	31 664	3	6–4Q(9) ^{3,20}	1.7369	35 992	6				
$v = 7$											
7–5Q(5) ³	1.7784	36 591	3								

Notes: ^a Maximum signal-to-noise ratio in the line image. In case of blends, the reported number refers to the sum of the blended lines (unless the emission comes from different zones of the bow).

¹ Blends with [Fe II] $a^2H_{11/2}-a^2G_{9/2}$;

² contaminated by atmospheric absorption;

³ detected in the whole bow;

⁴ blends with 4–2S(4);

⁵ blends with 3–1Q(2);

⁶ blends with HI 4–9;

⁷ blends with 3–1O(9);

⁸ blends with 6–4Q(9), HI 4–10;

⁹ blends with 6–4O(4);

¹⁰ blends with 4–2S(3);

¹¹ blends with 2–1S(9);

¹² blends with 2–0Q(9);

¹³ blends with 4–2S(0);

¹⁴ blends with [Fe II] $a^4D_{7/2}-a^4F_{9/2}$;

¹⁵ blends with 3–1Q(5);

¹⁶ blends with 3–1S(0);

¹⁷ blends with 2–0Q(2);

¹⁸ blends with 5–3Q(7);

¹⁹ blends with 4–2O(4);

²⁰ blends with 2–1S(13), HI 4–10;

²¹ blends with 2–1S(19).

line, however, neither evident discrepancies in the different computations of the Einstein coefficients (all the available lists give similar values, see Sect. 3.1.1) nor observational biases (e.g. extinction, blending with other lines) are able to explain the disagreement with the other ratios.

3.1.4. [FeII] abundance

The gas-phase Fe abundance $x(\text{Fe})$ is a measure of the shock efficiency in disrupting the cores of the dust grains where iron is locked in quiescent conditions (e.g. May et al. 2000). Estimates of $x(\text{Fe})$ in shock environments so far have given sparse results, from values close to solar abundance (e.g. Beck-Winchatz et al. 1996), up to intermediate (Nisini et al. 2002) and very high depletion factors (Mouri & Taniguchi 2000; Nisini et al. 2005).

A powerful way to estimate the percentage of gas-phase iron (δ_{Fe}) based on [Fe II]/[P II] line ratios has been proposed by Oliva et al. (2001). Since phosphorus and iron have similar ionisation potentials and radiative recombination coefficients, they are expected to be in the first ionised state in comparable percentages; moreover, the near-IR lines of Fe II and P II have similar excitation energies and critical densities and therefore are excited in similar physical conditions. Hence, [Fe II]/[P II] line ratios are good indicators of the relative abundance of the two species, and more specifically, because phosphorus is a non-refractory species, the Fe II/P II relative abundance should directly give an estimate of the degree of iron depletion. In HH99B

two [P II] lines are detected, at 1.1471 and 1.1885 μm , this latter barely blended with an [Fe II] line (see Table 1). Oliva et al. derive

$$\frac{x(\text{Fe})}{x(\text{P})} \simeq 2 \times \frac{I([\text{Fe II}]1.257)}{I([\text{P II}]1.188)} \simeq \frac{I([\text{Fe II}]1.257)}{I([\text{P II}]1.147)}. \quad (1)$$

This equation, as stated by the authors, is accurate to within a factor of 2 for all temperatures and densities expected within the shock. By assuming a solar Fe/P abundance ratio of ~ 120 (Asplund et al. 2005), we derived a map of the percentage of gas-phase iron (see Fig. 10). A strong decrease in the percentage of gas-phase iron occurs from the bow head (70%) towards the zones behind (up to 20%), with an average uncertainty of about 15%, estimated from the propagation of the errors in both the considered images. Notably, theoretical predictions for the degree of iron depletion as a function of the shock velocity (Jones 2000) imply that it should exceed 100 km s^{-1} for $\delta_{\text{Fe}} \gtrsim 0.20$, a condition verified in our case even in the bow flanks.

3.2. H₂ analysis

3.2.1. Extinction map

Looking at the line images of Fig. 1, it is evident that the bulk of the H₂ emission comes from the bow flanks. Since these parts of the bow are not covered in the extinction map obtained with [Fe II] lines (see Fig. 6), this cannot be used to de-redden the

Table 2. Ionic lines observed in HH99B.

Ionic lines							
Line id.	λ_{vac} (μm)	E_{up} (K)	S/N_{max}^a	Line id.	λ_{vac} (μm)	E_{up} (K)	S/N_{max}
[Fe II] lines ^b							
a⁴D_{7/2}–a⁶D_{9/2}	1.2570	11 446	700	a⁴D_{1/2}–a⁶D_{3/2}	1.2525	12 729	20
a⁴D_{7/2}–a⁶D_{7/2}	1.3209	11 446	130	a⁴D_{1/2}–a⁶D_{1/2}	1.2707	12 729	24
a⁴D_{7/2}–a⁴F_{5/2}	1.9541	11 446	7	a⁴D_{1/2}–a⁴F_{5/2}	1.6642	12 729	18
a⁴D_{7/2}–a⁴F_{9/2} ¹	1.6440	11 446	720	a⁴D_{1/2}–a⁴F_{3/2}	1.7454	12 729	21
a⁴D_{7/2}–a⁴F_{7/2}	1.8099	11 446	99	a⁴P_{5/2}–a⁴D_{5/2}	1.9675	19 387	20
a⁴D_{5/2}–a⁶D_{9/2}	1.1916	12 074	7	a⁴P_{5/2}–a⁴D_{1/2} ²	2.1609	19 387	5
a⁴D_{5/2}–a⁶D_{7/2}	1.2489	12 074	17	a⁴P_{3/2}–a⁴D_{7/2}	1.7489	19 673	9
a⁴D_{5/2}–a⁶D_{5/2}	1.2946	12 074	70	a⁴P_{1/2}–a⁴D_{5/2}	1.8139	20 006	6
a⁴D_{5/2}–a⁶D_{3/2}	1.3281	12 074	42	a²G_{9/2}–a⁴D_{7/2}	1.2675	22 797	2
a⁴D_{5/2}–a⁴F_{9/2}	1.5339	12 074	30	a²G_{7/2}–a⁴D_{7/2} ³	1.1885	23 552	16
a⁴D_{5/2}–a⁴F_{7/2}	1.6773	12 074	157	a²P_{3/2}–a⁴P_{5/2}	2.0466	26 417	4
a⁴D_{5/2}–a⁴F_{5/2}	1.8005	12 074	35	a²P_{3/2}–a⁴P_{3/2}	2.1334	26 417	5
a⁴D_{3/2}–a⁶D_{3/2}	1.2791	12 489	41	a²P_{3/2}–a⁴P_{1/2}	2.2442	26 417	4
a⁴D_{3/2}–a⁶D_{1/2}	1.2981	12 489	23	a²H_{11/2}–a²G_{9/2} ⁴	2.2244	29 265	21
a⁴D_{3/2}–a⁴F_{7/2}	1.5999	12 489	46	a²H_{9/2}–a²G_{9/2}	2.0157	29 934	5
a⁴D_{3/2}–a⁴F_{5/2}	1.7116	12 489	13	a²H_{9/2}–a²G_{7/2}	2.2541	29 934	35
a⁴D_{3/2}–a⁴F_{3/2}	1.7976	12 489	36	b⁴P_{1/2}–a⁴P_{3/2}	1.1446	32 242	2
H lines							
3–5 (Pa β)	1.2822	151 492	21	4–11	1.6811	156 499	6
4–14	1.5884	156 999	3	4–10 ⁵	1.7367	156 226	6
4–13	1.6114	156 870	4	4–9 ⁶	1.8179	155 855	6
4–12	1.6412	156 708	3	4–7 (Br γ)	2.1661	154 583	12
Other lines							
He I ¹ P ₁ – ¹ S ₀	2.0587	246 226	3	[Ti II] a ² F _{5/2} –a ⁴ F _{3/2} ¹⁰	2.1605	6652	5
He I ³ D– ³ P ⁷	2.0607	282 101	8	[Ti II] a ² F _{7/2} –a ⁴ F _{9/2}	2.2201	7040	5
He I ³ P ₀ – ³ D ⁷	1.9522	289 992	5	[Ti II] a ² D _{5/2} –a ⁴ F _{5/2}	1.1560	12 570	2
[P II] ² D ₂ – ³ P ₁	1.1471	12 764	5	[Ti II] a ⁴ P _{3/2} –b ⁴ F _{7/2}	1.2036	13 506	2
[P II] ² D ₂ – ³ P ₂ ⁸	1.1886	12 764	16	[Ti II] a ² P _{3/2} –b ⁴ F _{3/2}	1.1028	14 340	2
[Co II] b ³ F ₄ –a ⁵ F ₅ ⁹	1.5474	14 119	5	[Ti II] a ² H _{11/2} –a ² F ₂	1.2695	17 729	3

Notes: ^a Maximum signal-to-noise ratio in the line image. In case of blends the reported number refers to the sum of the blended lines (unless the emission comes from different zones of the bow). ^b Lines coming from the same upper level are grouped, and the first term of each group is evidenced with bold-face characters.

¹ Blends with 3–1O(7);

² blends with [Ti II] a²F_{5/2}–a⁴F_{3/2} (fundamental transition);

³ blends with [P II] ¹D₂–³P₂;

⁴ blends with 1–0S(0);

⁵ blends with 2–1S(13), 6–4Q(9);

⁶ blends with 2–1S(8);

⁷ multiplet;

⁸ blends with [Fe II] a²G_{7/2}–a⁴D_{7/2};

⁹ tentative identification;

¹⁰ blends with [Fe II] a⁴P_{5/2}–a⁴D_{1/2}.

H₂ emission. Therefore, as a first step in the H₂ line analysis, we derived a new extinction map. Out of a number of ratios of lines coming from the same upper level, we considered only the three ratios (1–0S(1)/1–0Q(3), 2–0S(1)/2–1S(1), and 2–0Q(3)/2–1S(1)) of lines detected at S/N per pixel larger than 5 over the whole emission region. Since the one at the highest S/N (1–0S(1)/1–0Q(3)) suffers from the poor atmospheric transmission at 2.42 μm of the 1–0Q(3), we used the other two ratios as calibrators and the 1–0S(1)/1–0Q(3) ratio to probe the differential extinction along the shocked region. The Rieke & Lebofsky (1985) extinction law was adopted. The final map is shown in Fig. 11, where the covered zone somewhat complements the A_V map constructed from [Fe II] lines, with a partial spatial overlap in the areas corresponding to knots B3 and B1 of D99. The A_V values typically range from 1 to 4 mag, in substantial agreement with those inferred from [Fe II] emission, so that this result demonstrates that the reddening *within* the shock does not change significantly and that the A_V variations

mainly arise from the foreground material inside the cloud. Our result contrasts with the general trend observed both in other Herbig-Haro objects (e.g. Nisini et al. 2002; Giannini et al. 2004) and in HH99B itself (MC04), where the extinction computed from [Fe II] lines is systematically higher than probed with H₂ lines. This may stem from the extinction being in these cases computed from the 1.257 μm /1.644 μm ratio, for which the A coefficients of NS were been adopted (see Sect. 3.1.1).

3.2.2. Temperature map

The temperature of the molecular gas can be obtained from a Boltzmann diagram (e.g. Gredel 1994), plotting $\ln(N_{v,J}/g_J)$ against $E_{v,J}/k$. Here $N_{v,J}$ (cm^{-2}) is the column density of the level (v, J), $E_{v,J}$ (K) its excitation energy, and $g_J = (2J+1)(2I+1)$ the statistical weight (here we assume that $I = 0, 1$ for para- and ortho-H₂). If the gas is thermalised at a single temperature, the

Fig. 5. $I(1.257 \mu\text{m})/I(1.644 \mu\text{m})$ vs. $I(1.321 \mu\text{m})/I(1.644 \mu\text{m})$ ratios measured in different objects (depicted with different symbols/colours). The HH99B-SINFONI data (red squares) have been computed in pixels where the S/N of each of the three lines is higher than 100, while other data are literature observations where $S/N \geq 30$. Intrinsic line ratios predicted theoretically (Q-SST = Quinet et al. 1996 – SuperStructure; Q-HFR = Quinet et al. 1996 – Relativistic Hartree-Fock; NS = Nussbaumer & Storey 1988), along with the observational point (SH) by Smith & Hartigan (2006), are labelled. Green dashed curves represent the extinction law by Rieke & Lebofsky (1985), starting from different theoretical points; open squares refer to $A_V = 0, 5, 10$ mag. The same extinction law (in red) has been applied to the $A_V = 0$ mag point derived from SINFONI data. The latter has been derived by applying to the average of the HH99B points (black cross) a visual extinction of 1.8 mag, as estimated from the $\text{Pa}/\text{Br}\gamma$ ratio (see text). References: HH99B – SINFONI: this work; HH111-, HH240-, HH120-SofI: Nisini et al. (2002); HH240- ISAAC: Calzoletti et al. (2008); HH99B – ISAAC: M^cCoey et al. (2004); HH1 – SofI: Nisini et al. (2005); HH54 – ISAAC: Giannini et al. (2007); HH34 – SofI: Podio et al. (2006); HH135 – SofI: Gredel (2006); Orion bar – SofI: Walmsley et al. (2000); P Cygni – Spex: Smith & Hartigan (2006).

data points align onto a straight line, whose slope gives the gas temperature. In this diagram, points that refer to transitions from the same upper level do overlap each other, once corrected for extinction effects.

We applied this method to all the pixels of the H_2 images, and the resulting map is shown in Fig. 12, where temperature contours are given in units of 10^3 K. Three results can be taken from this map:

- A temperature gradient from ≈ 2000 K up to 6000 K occurs from the receding parts of the shock towards the head. We underline that this gradient can be traced because of the very large number of H_2 lines detected, which cover the Boltzmann diagram up to excitation energies of $\sim 38\,000$ K, therefore sensitively widening the dynamical range of temperatures typically probed with H_2 near-infrared lines;
- Two different behaviours in the Boltzmann diagram occur between the bow head and the flanks (see the insets in Fig. 12): H_2 appears fully thermalised (at $T \sim 5000$ K) at the bow head (hence the contours here give the gas

Fig. 6. Extinction map obtained from $[\text{Fe II}]$ lines where contours from $A_V = 1$ mag to $A_V = 4$ mag are shown. The NS Einstein A coefficients have been adopted.

Fig. 7. De-reddened contours of $1.257 \mu\text{m}$ intensity, overlaid with the image acquired in the same line.

temperature directly), while a curvature exists among the points in the southern flank diagram, so that at least two temperature components can be traced. In these parts of the bow, the contours indicate the *average* of these temperatures. The outlined behaviour can be generalised to the whole bow structure and likely reflects, from one side, that fluorescence can be discarded as a possible excitation mechanism, since it implies strong departures from thermalisation (Black & van Dishoeck 1997), and, from the other side, that different shock mechanisms are at work. In fact, the response of the level populations to the shock parameters can be seen in the Boltzmann diagram. Roughly speaking, an enhancement of the shock velocity increases the rate of collisions that vibrationally excite the H_2 molecules and favours thermodynamical equilibrium; thus, the thermalisation observed along the head would testify to the presence of a fast shock. If this were the case, a C-type shock should be favoured, otherwise H_2 could not survive (at high temperatures) against dissociation (e.g. Le Bourlot et al. 2002; Flower et al. 2003). The alternative possibility that the observed H_2 emission arises from re-forming H_2 onto dust grains can be reasonably discarded. In

Fig. 8. Electron density map as derived from [Fe II] line ratios. Contours are in units of 10^3 cm^{-3} .

Fig. 9. $[I_{1.257}/I_\lambda]_{\text{obs}}/[I_{1.257}/I_\lambda]_{\text{mod}}$ plotted vs. the electronic temperature for four [Fe II] lines. The results for the Fe NLTE model at 16 and 19 levels are shown for comparison.

fact, the timescale of this process is of the order of $10^{17}/n \text{ s}^{-1}$ (Hollenbach & McKee 1979), with n the density of the gas after the compression due to the shock passage. For reasonable values of this parameter (10^4 – 10^7 cm^{-3}), and assuming a velocity of the downstream gas of the order of 10 km s^{-1} , the distance covered by the gas at the bow head should be between 10^{16} and 10^{19} cm , definitively longer than the linear dimension of knot B0, i.e. $\sim 5 \times 10^{15} \text{ cm}$;

- A marked difference in the column density of the warm H_2 (from the intercept of the straight line) emerges from the same Boltzmann diagrams. For example, from the insets of Fig. 12 we derive $N(\text{H}_2) = 2 \times 10^{17} \text{ cm}^{-2}$ and $3 \times 10^{16} \text{ cm}^{-2}$ at the flank and at the bow head, respectively. If the same shock lengths are assumed for these regions, then about 85% of the molecular gas must get destroyed in the most excited part of the shock (although H_2 emission is still observed).

Fig. 10. Map of the percentage of iron in gas phase overlaid with the intensity contours of the [Fe II] $1.257 \mu\text{m}$ line.

Fig. 11. Extinction map as derived from H_2 line ratios. Contours from $A_V = 1$ to 4 mag are shown.

3.3. H analysis

At the bow head we observe hydrogen recombination lines of the Brackett series along with the $\text{Pa}\beta$ line. The S/N ratio of these lines, except for $\text{Br}\gamma$ and $\text{Pa}\beta$, is so low, however, that detailed modelling is prohibitive. Thus, we used only the $\text{Pa}\beta/\text{Br}\gamma$ ratio to independently estimate the extinction. Assuming case B recombination (Storey & Hummer 1995), we obtain $A_V = 1.8 \pm 1.9 \text{ mag}$.

More interesting parameters, i.e. the hydrogen fractional ionisation x_e and the hydrogen post-shock density $n_{\text{H}} = n_e/x_e$, are obtainable from the observed intensity ratio $[\text{Fe II}] 1.257/\text{Pa}\beta$. As

Fig. 12. Temperature map (in 10^3 K) as derived from H_2 line ratios. As an example, we show the rotational diagrams at two points of the bow: while at the bow head H_2 appears thermalised at ($T \sim 5000$ K), and two temperature components co-exist in the southern flank, with an average temperature (corresponding to the point shown in the map) of ~ 2800 K.

described in detail in Nisini et al. (2002), under the assumption that iron is singly ionised, such a ratio can be expressed as

$$x_e = \delta_{Fe} (Fe/H)_\odot \left(\frac{[Fe II]_{1.257}}{Pa\beta} \right)^{-1} \frac{\epsilon_{[Fe II]_{1.257}}}{\epsilon_{Pa\beta}} \quad (2)$$

with δ_{Fe} the gas-phase iron fraction with respect to the solar Fe abundance $(Fe/H)_\odot$ and $\epsilon_{[Fe II]_{1.257}}$ and $\epsilon_{Pa\beta}$ (in $\text{erg cm}^3 \text{s}^{-1}$) the emissivities of the two lines, taking $\epsilon_{Pa\beta}$ from Storey & Hummer (1995). This quantity was computed for the physical conditions derived at the bow head, i.e. $T = 16000$ K, $n_e = 6 \times 10^3 \text{ cm}^{-3}$, $\delta_{Fe} \sim 0.7$, having taken $(Fe/H)_\odot = 2.8 \times 10^{-5}$ (Asplund et al. 2005). This leads to $x_e \sim 0.4$ – 0.5 and n_H between 0.8 and $1.4 \times 10^4 \text{ cm}^{-3}$. In the receding parts of the shocks, the fractional ionisation cannot be computed directly, since we have no estimates for the electron temperature. However, under the reasonable assumption that $T_e \lesssim 10000$ K, a sharp decrease in x_e is expected: for example, for the regions where $\delta_{Fe} = 0.3$ – 0.4 , we find $x_e \sim 0.2$ – 0.3 . These estimates agree with those inferred along other Herbig-Haro objects through optical-line diagnostics (e.g. Bacciotti & Eisloffel 1996; Hartigan & Morse 2007) and with those inferred in a number of jets by combining optical and infrared observations (Nisini et al. 2005; Podio et al. 2006).

4. Kinematical properties

4.1. H_2

In this section we intend to characterise the kinematical parameters of the shock(s) in HH99B. This topic has already been discussed by D99, so here we compare our results with those found in that work. The higher spectral resolution ($R \sim 15 \text{ km s}^{-1}$) of D99, obtained with echelle spectroscopy, has revealed that the peak velocity of the H_2 $2.122 \mu\text{m}$ line moves progressively

from slightly blue-shifted values near the shock front towards red-shifted values in the flanks and has been interpreted in the framework of a receding bow-shock oriented with respect to the line of sight of about 45° .

Nominally, the spectral resolution of our K band observations would not permit us to reveal variations close to those measured by D99. This limitation, however, is partially compensated by the very high S/N ratio at which we detect the $2.122 \mu\text{m}$ line. A trend in both the peak velocity and in the profile shape can be followed along the bow structure, although we cannot give precise numerical estimates for the line parameters (v_{peak} , FWHM). Our results are presented in Fig. 13, where the contours of the $2.122 \mu\text{m}$ line intensity (de-reddened) have been superposed on the v_{peak} map.

Overall, our results confirm those of D99: the line profile presents a blue-shifted component towards the shock front at the bow head (B0). The opposite occurs along the two flanks and especially along the edge of the B1 flank (not covered by the echelle spectra in D99), where the line peak is shifted $\sim +15 \text{ km s}^{-1}$ with respect to the line profile at the head. Analogous to the spectra of D99, the $2.122 \mu\text{m}$ profile does not show double-peaked components, as generally expected for a parabolic bow structure (Schultz et al. 2005), though it does become wider near the centre of the bow, where the opposite sides are seen in projection. Here the observed $FWHM_{\text{obs}}$ is 85 – 105 km s^{-1} , that, deconvolved with the instrumental profile, measured on atmospheric OH lines, roughly gives an intrinsic line width of ~ 20 – 40 km s^{-1} . The agreement with previous observations is also maintained along the bow flanks, where the profile width becomes narrower, decreasing toward the spectral resolution limit on the intrinsic width of $\sim 20 \text{ km s}^{-1}$. As for the line peak, a sudden increase in $FWHM_{\text{obs}}$ is registered at the edge of the southern flank, where we measure up to $\sim 115 \text{ km s}^{-1}$, i.e. an intrinsic width of $\sim 70 \text{ km s}^{-1}$. This is close to the maximum

Fig. 13. Local standard of rest (LSR) velocity map of the $2.122\ \mu\text{m}$ line peak, with superimposed line intensity contours. We indicate with a white line the diameter $2R_{\text{dis}}$ of the last cap beyond which the bulk of H_2 is dissociated (see Sect. 4.2). Insets show the line profile observed at the bow head (*top left*), in the southern flank (*bottom left*), and at the bow centre (*bottom right*). Blue and red asymmetries are visible at the bow head and along the flanks, while the line is symmetric toward the centre. The instrumental profile, measured on OH atmospheric lines, is shown for comparison (red dashed line).

shock velocity ($\sim 80\ \text{km s}^{-1}$) at which H_2 can survive against dissociation, predicted by the C-shock model by Le Bourlot et al. (2002). This last topic will be discussed in the next section.

4.2. [Fe II]

We performed the kinematical analysis of the ionic gas component on the two brightest [Fe II] lines at 1.257 and $1.644\ \mu\text{m}$. Both appear resolved in velocity and give similar results for the line profile shape (which is Gaussian across the whole bow), the intrinsic line width, the peak position, and the FWZI. The last result gives a direct measure of the shock speed at the bow apex (Hartigan et al. 1987): we obtain $v_{\text{bow}} = 115 \pm 5\ \text{km s}^{-1}$, which agrees with the prediction by D99 ($80\text{--}120\ \text{km s}^{-1}$) derived from the overall shape of the bow and the characteristics of the $\text{H}_2\ 2.122\ \mu\text{m}$ line profile.

In Fig. 14 we show the radial velocity map of the $1.644\ \mu\text{m}$ line, which appears red-shifted over the whole bow structure, the maximum shift occurring towards the image centre. We interpret this behaviour as a geometrical effect due to the inclination of the bow with respect to the line of sight. Indeed, if the bow is observed at a certain angle $\alpha \neq 0^\circ, 180^\circ$, the peak of the radial velocity component is seen offset from the bow apex. Following the procedure described in Appendix A, we are able to express the projected distance (D') between the emission and the radial velocity peaks as a function of α and the H_2 breakdown velocity (v_{dis}), once the relationship between this latter and the parameter b regulating the bow (parabolic) shape is defined. The result is depicted in Fig. 15. Interestingly, we found α values close to that ($\sim 45^\circ$) inferred by D99 for a range of v_{dis} between 70 and

$90\ \text{km s}^{-1}$. These values can be considered as an indirect measurement of a parameter whose theoretical predictions have been widely discussed over the past decades: a first value of $24\ \text{km s}^{-1}$ was inferred by Kwan (1977), subsequently Draine et al. (1983) found $v_{\text{dis}} = 50\ \text{km s}^{-1}$, a result confirmed by Smith & Brand (1990) and Smith (1991). More recently, Le Bourlot et al. (2002) have shown that v_{dis} can increase up to $80\ \text{km s}^{-1}$ for values of the pre-shock density around $10^3\ \text{cm}^{-3}$. Our measurement therefore agrees with the last prediction. Moreover, $v_{\text{dis}} \sim 80\ \text{km s}^{-1}$ is consistent with the *FWHM* of the $2.122\ \mu\text{m}$ line profile measured in the southern flank (Sect. 4.1), and it reinforces the hypothesis that a fast, continuous shock is responsible for the excitation of the molecular gas at the apex of the bow (Sect. 3.2.2).

5. Concluding remarks

We have presented bi-dimensional, deep near-infrared spectral images of the bow shock HH99B. These have allowed us, for the first time, to accurately derive the physical parameters of both the molecular and ionic gas components (summarised in Table 3, where our results are compared with those derived in previous works) and, at the same time, to characterise the geometry and the kinematical properties of the flow. The main results of this study are the following.

- More than 170 emission lines have been detected, mainly vibrational H_2 and [Fe II] lines, many of them never observed before in a Herbig-Haro object. In addition, transitions of hydrogen and helium recombination and fine structure lines of [P II], [Ti II], and possibly [Co II] were observed.

Fig. 14. *Left panel:* local standard-of-rest (LSR) velocity map of the $1.644 \mu\text{m}$ line peak, with superimposed line intensity contours. The line is red-shifted along the bow-structure, with a peak at about $+70 \text{ km s}^{-1}$. The projection D' along the line of sight of the distance between the line emission peak and the maximum radial velocity is shown, together with the diameter $2 R_{\text{dis}}$ (see caption of Fig. 13). *Right panel:* schematic view of the parabolic geometry assumed for the bow-shock. The apex coincides with the origin of the coordinate system. $R = \sqrt{x^2 + y^2}$, is the radius at the distance z along the bow axis, ϕ the azimuthal angle around the z -axis, θ the angle between the bow direction and the tangent to the parabolic surface (at each θ the shock velocity at the apex, v_b , is de-composed in $v_{\parallel}$ and $v_{\perp}$), and α is the angle, lying on the $x - z$ plane, between the z -axis and the line of sight. D is the distance between the line emission peak and the maximum radial velocity and D' its projection onto the sky plane.

Table 3. Physical parameters estimated in HH99B.

Parameter	This work	MC04	D99
$A_V(\text{Fe II})$ (mag)	1–4	4–10	–
$A_V(\text{H}_2)$ (mag)	2–4	<4	<4.6
$A_V(\text{H})$ (mag)	~ 2	–	–
n_e (cm^{-3})	$3\text{--}6 \times 10^3$	–	–
T_e (K)	$\leq 17\,000$	–	–
T_{H_2} (K)	2500–6000	2000–4000	–
N_{H_2} (cm^{-2})	$3 \times 10^{16}\text{--}2 \times 10^{17}$	–	–
$\delta_{\text{Fe II}}$	0.2–0.7	0.25	–
x_e	0.2–0.5	–	–
n_{H} (cm^{-3})	$\sim 10^4$ (post-shock)	10^4 (pre-shock)	–
v_{bow} (km s^{-1})	110–120 ([Fe II])	50 ([Fe II])	80–120 (H_2)
inclination angle ($^\circ$)	40–60	–	45

- A clear bow-shape morphology emerges from the line intensity maps. As shown in Figs. 2–4, [Fe II], and other ionic emission peaks definitely at the bow head (B0), also strong in the knot B2 immediately behind. In contrast, H_2 emission delineates the bow flanks, peaking in the knots B1 and B3. Notably, the H_2 lines with the highest excitation energy ($E_{\text{up}} \gtrsim 30\,000 \text{ K}$) show a different morphology, which is strong towards the bow head. This implies that H_2 still survives in this zone, in spite of the significant temperature enhancement there.
- Extinction maps were derived from the analysis of both [Fe II] and H_2 lines. These give similar results, with A_V ranging between 1 and 4 mag.
- A detailed electron density map was obtained in the framework of NLTE approximation for [Fe II] line emission. This remains almost constant in the [Fe II] emission zone, peaking towards the bow head. From the same emission, we were

able to probe a variation in the electron temperature, which falls from $\sim 16\,000 \text{ K}$ at the apex to less than $10\,000 \text{ K}$ in the receding parts of the bow.

- An iron depletion degree not higher than 30% was inferred at the bow apex, which testifies in favour of a J-type shock as the main excitation mechanism in this part of the bow. In this same zone, we infer a fractional ionisation of ~ 0.6 and a post-shock density of $\sim 10^4 \text{ cm}^{-3}$.
- Analysis of H_2 line emission allowed us to probe the molecular temperature variation. We find that at the bow apex thermalisation has been reached at $T \sim 6000 \text{ K}$, likely due to the presence of a fast, non-dissociative shock. In contrast, different temperature components are simultaneously present along the flanks. A decrease in about a factor of ten is registered in the H_2 column density going from knots B1/B3 toward knot B0. Both these circumstances are not accounted for by models that have attempted to interpret the H_2

Fig. 15. Projection over the sky plane of the distance between the [Fe II] 1.644 μm emission peak and the maximum radial velocity, plotted against the bow inclination angle α . The hatched area defines the uncertainty on D' , estimated as the maximum and minimum distance between the 1.644 μm line peak and the points where the maximum shift in velocity is registered (those coloured in red in Fig. 14, left panel). The curves refer to different assumptions for the H_2 breakdown speed, v_{dis} , having measured the shock velocity at the bow apex, v_{bow} and the radius R_{dis} (see Appendix A). The observations are matched for v_{dis} between 70 and 90 km s^{-1} .

emission on HH99B on the basis of fewer lines. Therefore, the conclusions of these models should be tested in the light of this new piece of information.

- From the brightest [Fe II] and H_2 lines, we were able to probe the kinematical properties (e.g. shock velocity) of the shocked gas. In particular, we confirm the result by D99 according to which HH99 is a red-shifted, receding bow.
- The radial velocity map of [Fe II] emission was interpreted in the framework of the bow geometry. From this map we have consistently inferred the bow inclination angle and defined a range of 70–90 km s^{-1} for the H_2 breakdown velocity. These values agree with the prediction of Le Boulrot et al. (2002) of v_{dis} up to 80 km s^{-1} . We propose our method as a valuable tool in deriving the jet inclination angle (if greater than 10–20°) in cases where proper motion is unknown.
- The kinematical parameters of the [Fe II] emission estimated in this work do not confirm the model predictions by MC04. In particular, the argument that the [Fe II] lines originate in a pure J-type shock with $v_{\text{shock}} \sim 50 \text{ km s}^{-1}$ contrasts with our measure of $v_{\text{shock}} \sim 110\text{--}120 \text{ km s}^{-1}$. Thus, the modelling of the [Fe II] emission may have to be revised.

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Appendix A: Derivation of inclination angle and H_2 breakdown velocity

With reference to Fig. 14, right panel, we assume that the bow has a parabolic geometry ($z = R^2/2b$), where the apex coincides with the origin of the coordinate system. There, $R = \sqrt{x^2 + y^2}$, is the radius at the distance z along the bow axis, ϕ the azimuthal

angle around the z -axis, θ the angle between the bow direction and the tangent to the parabolic surface, and α the angle, lying on the $x - z$ plane, between the z -axis and the line of sight. The last can be inferred by measuring, in the radial velocity map (Fig. 14, left panel), the projection D' over the sky plane of the distance between the line emission peak and the maximum radial velocity ($D' = 10 \pm 2$ pixels). We have

$$D' = D \cos(\chi - \alpha) = \sqrt{z_{\text{max}}^2 + 2z_{\text{max}}b} \times \cos(\chi - \alpha) \quad (\text{A.1})$$

where z_{max} is the distance along the z -axis at which the radial velocity reaches its maximum. We first estimated the b parameter. Since the molecular hydrogen does not emit over the entire bow surface, there is a leading edge that divides the bow into two different zones: a dissociation cap, beyond which the emission comes from atomic/ionic elements, and a molecular hydrogen emitting flank. It is therefore possible to define as z_{dis} the position along the z -axis where the leading edge plane is located. Certainly it depends on the shock velocity at the bow apex, v_{bow} , on the H_2 breakdown velocity, v_{dis} , and on the shape of the bow surface. Setting $v_{\text{dis}} = v_{\text{bow}} \sin \theta_{\text{dis}}$ and, since for a generic angle θ , $\tan \theta = dR/dz$:

$$v_{\text{dis}} = v_{\text{bow}} \frac{dR/dz}{\sqrt{1 + \left(\frac{dR}{dz}\right)^2}} \bigg|_{z=z_{\text{dis}}} \quad (\text{A.2})$$

Substituting the parabolic equation in this formula, we get

$$z_{\text{dis}} = \frac{b}{2} \left[\left(\frac{v_{\text{bow}}}{v_{\text{dis}}} \right)^2 - 1 \right] \quad (\text{A.3})$$

and

$$b = \frac{R_{\text{dis}}^2}{2z_{\text{dis}}} = \frac{R_{\text{dis}}}{\sqrt{\left(\frac{v_{\text{bow}}}{v_{\text{dis}}}\right)^2 - 1}} \quad (\text{A.4})$$

In Eq. (A.4), R_{dis} is the radius of the cap beyond which H_2 dissociates, which we have measured both from the 2.122 μm (Fig. 13) and 1.644 μm emission contours (Fig. 14). Both of them give $R_{\text{dis}} \sim 20$ pixels. We also estimated $v_{\text{bow}} = 115 \pm 5 \text{ km s}^{-1}$ from the FWZI of the 1.644 μm (Hartigan et al. 1987). Substituting these values in Eq. (A.4), we have b as a function of v_{dis} only, which we take as a free parameter.

The above expression of b is then substituted in the parabolic equation to derive z_{max} :

$$z_{\text{max}} = \frac{b}{2} \left[\left(\frac{v_{\text{bow}}}{v_{\text{max}}} \right)^2 - 1 \right] = \frac{b}{2} \left[\frac{1}{\sin^2 \theta_{\text{max}} - 1} \right] \quad (\text{A.5})$$

Following Hartigan et al. (1987) and considering that the bow is seen from the back (D99), we get $\theta_{\text{max}} = \pi/2 - \alpha/2$. Thus

$$z_{\text{max}} = \frac{b}{2} \left[\left(\frac{1}{\cos(\alpha/2)} \right)^2 - 1 \right] \quad (\text{A.6})$$

In conclusion, from Eqs. (A.4) and (A.6) and by measuring χ from simple geometrical considerations, we are able to express in Eq. (A.1) D' only as a function of α and v_{dis} , which have been routinely varied to match our measurement of D' , as shown in Fig. 15.

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