Near-infrared, IFU spectroscopy unravels the bow-shock HH99B**

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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-SPHIFI IFU spectroscopy (R ∼ 2000–4000) between 1.10 and 2.45 μm 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 ≤ 7, E_up ≤ 38 000 K) and [Fe II] (E_up ≤ 30 000 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 H₂ 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. H₂ 2.122 μm and [Fe II]1.644 μm), 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 μm 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 Av is found at the bowhead (Av ∼ 4 mag) while diminishing along the flanks. The electron density increases from ∼3 × 10³ cm⁻³ in the receding parts of the shock to ∼6 × 10³ cm⁻³ in the apex, where we estimate a temperature of ∼16 000 K from [Fe II] line ratios. Molecular gas temperature is lower in the bow flanks (∼3000 K), then progressively increases toward the head up to T ∼ 6000 K. In the same zone, we are able to derive the iron gas-phase abundance (∼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 (∼1 × 10⁴ cm⁻³). The kinematical properties derived for the molecular gas substantially confirm earlier ones, while new information (e.g. u_shock ∼ 115 km s⁻¹) is provided for the shock component responsible for the hydrogen emission. We also provide an indirect measure of the H₂ breakdown speed (between 70 and 90 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 role 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
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 Bourlot 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., Eisloffel 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 (Fe II) 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 prototypical bow-shock, namely the Herbig-Haro object HH99B. This is located in the RCrA molecular core at $d \sim 130$ pc (Marraco & Rydgen 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 McClay 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-SPITFI 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 $\mu$m), H (1.45–1.85 $\mu$m) and K (1.95–2.45 $\mu$m) 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 de-reddened 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. H$_2$ 2.122 µm and [Fe II]1.644 µm), which are observed at $S/N$ ratios of $\sim 10^{-2}$–$10^{-1}$. As a final step, images of lines observed in individual bands ([Fe II]1.257 µm and 1.644 µm in the $J$ and $H$ bands and H$_2$ 2.122 µm 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 H$_2$ 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 $E_{uv}$ 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 $E_{uv} \leq 30,000$ K is present only along the bow flanks, while lines with $E_{uv} \geq 30,000$ K are observed in the whole shock, peaking at the bow head. Therefore, two main results emerge: (i) molecular hydrogen also survives where ionization 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 $E_{uv} \leq 30,000$ K. As for H$_2$, two groups of lines are identified: those with $E_{uv} \leq 13,000$ K, which come for the $a^4D$ 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], [C II], and [Ti II] are detected. Other fine structure lines commonly observed in Herbig-Haro objects (e.g. [C I] at 0.98 µm, [N I] at 1.04 µm, [S II] at 1.03 µm, Nisini et al. 2002) are not covered with SINFONI. In fact, the first wavelength in the $J$ band is $\lambda = 1.10$ µm, 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 µm and 0.86 µm, 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 ($PA = 32.4^\circ$ and 329.5$^\circ$, 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], H$_2$, 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 [FeII] 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 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 µm and 1.257 µm lines (both coming from the level $a^4D_{3/2}$ with $E_{uv} = 11,446$ 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 µm and a by factor of 1.4 for a line at 2 µm), but becomes critical at optical wavelengths (the intensity grows by a factor of 33.6 at 0.5 µm).

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 $I(1.257 \mu m)/I(1.644 \mu m)$ vs. $I(1.321 \mu m)/I(1.644 \mu m)$ 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 law 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 along the 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 $\mu$m/1.644 $\mu$m ratio is always smaller than derived from the 1.257 $\mu$m/1.644 $\mu$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 $\mu$m to 1.644 $\mu$m).
Fig. 1. Selected spectral images from our HH99B data-cube. Intensities are given on a colour scale. Offsets are from $\alpha_{2000} = 19^h02^m05.4^s$, $\delta_{2000} = -36^\circ54^\prime39^\prime$. A) $\text{H}_2$:1−0 S(1) at 2.122 $\mu$m. The locations of the knots labelled by D99 (B1, B2 and B3) and MC04 (B0) are indicated; B) $\text{H}_2$: 2−1O(7) at 1.758 $\mu$m; C) [Fe II]: $a^4D_{7/2} - a^4P_{9/2}$ at 1.644 $\mu$m. The black line defines the area where [Fe II] lines at $S/N > 100$ are detected and used to construct the plot of Fig. 5; D) [Fe II]: $a^4P_{3/2} - a^4D_{7/2}$ at 1.749 $\mu$m; E) H: Paβ at 1.282 $\mu$m; F) [P II]: $2^D_2 - ^3P_2$ at 1.188 $\mu$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 HH99B data are also inconsistent with the P Cygni 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 [Fe II] lines with other lines or telluric features. In this respect, the 1.644 $\mu$m line is close to both the $\text{H}_2$ line 3−1O(7) at 1.6453 $\mu$m (see Table 1 and Fig. 3) and a
telluric OH feature at 1.6442 μm (Lidman & Cuby 2000). This one was removed in the sky subtraction procedure, and its residuals estimated to affect the 1.644 μm flux by less than 0.5%. The H$_2$ line, coming from a low excitation level ($E_{\text{up}} \sim 19\ 000$ K), is observed only in the receding parts of the bow, hence is spatially separated from the 1.644 μm 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 arcsec$^2$ (marked in black in Fig. 1, middle left panel), an extinction gradient of $\sim 1$ 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 $A_V$ ($1.8 \pm 1.9$ mag) from the observed Pa/Br ratio (see Sect. 3.3). Both these circumstances prevent us from deriving an accurate measure of the

Fig. 2. $J$-band spectrum extracted in knots B3 (black) and B0 (red), over an area of 0.5 and 1.25 arcsec$^2$, respectively.
A rough estimate can however be obtained by de-reddening 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 μm/1.644 μm ratio and the Q-HFR coefficients for the 1.257 μm/1.644 μm 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
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 μm/1.644 μm 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 ~10 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 re-derived the same map from the 1.257 μm/1.644 μm 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 μm) increases by

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Fig. 4. As in Fig. 2 for the K band.
Table 1. H$_2$ lines observed in HH99B.

| Line id. | $\lambda_{\text{asc}}$ (Å) | $E_{\text{up}}$ (K) | $S/N_{\text{max}}$ | Line id. | $\lambda_{\text{asc}}$ (Å) | $E_{\text{up}}$ (K) | $S/N_{\text{max}}$ | Line id. | $\lambda_{\text{asc}}$ (Å) | $E_{\text{up}}$ (K) | $S/N_{\text{max}}$ |
|----------|-----------------|------------------|-----------------|----------|-----------------|------------------|-----------------|----------|-----------------|------------------|-----------------|
| 1−0S(0)$^1$ | 2.2233 | 6471 | 44 | 1−0S(7) | 1.7480 | 12818 | 65 | 1−0S(21)$^3$ | 1.7195 | 38136 | 7 |
| 1−0S(1) | 2.1218 | 6951 | 650 | 1−0S(8) | 1.7147 | 14221 | 70 | 1−0S(23) | 1.7801 | 42122 | 4 |
| 1−0S(2) | 2.0338 | 7584 | 48 | 1−0S(9) | 1.6877 | 15723 | 46 | 1−0Q(1) | 2.4066 | 6149 | 44 |
| 1−0S(3) | 1.9576 | 8365 | 46 | 1−0S(10) | 1.6665 | 17312 | 9 | 1−0Q(2) | 2.4134 | 6471 | 30 |
| 1−0S(5)$^2$ | 1.8358 | 10342 | 5 | 1−0S(18)$^3$ | 1.6586 | 32136 | 3 | 1−0Q(3) | 2.4237 | 6951 | 50 |
| 1−0S(6) | 1.7879 | 11522 | 30 | 1−0S(19)$^3$ | 1.6750 | 34131 | 8 | 1−0Q(4) | 2.4375 | 7584 | 18 |

$^1$Computed at selected seven intensity ratios (i.e. 0.10%) 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. $I_{1S(3)}/I_{1S(4)}, I_{1O(7)}/I_{1S(1)}, I_{1S(5)}/I_{1O(9)}, I_{2S(5)}/I_{2S(7)}, I_{1O(11)}/I_{2S(7)}, I_{1S(2)}/I_{1S(9)}, I_{2S(7)}/I_{1S(5)}$, involving lines close in wavelength (their differential extinction is negligible) and coming from levels with different critical densities (from $\sim 8 \times 10^5$ to $3 \times 10^7$ cm$^{-3}$) and similar excitation energy ($E_{\text{up}} < 10000 − 12000$ 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 [FeII]. Spontaneous rates are taken from NS, while energy levels and rates for electron collisions are adopted from Pradhan & Zhang (1993). Assuming $T_e = 10000$ K, we constructed the electron density map shown in Fig. 8. $n_e$ is about $2−4 \times 10^5$ cm$^{-3}$, with a peak up to $6 \times 10^6$ cm$^{-3}$ at the bow head$^2$. 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 arcsec$^2$ (see Fig. 1, middle right panel), we detected 13 lines at high excitation ($E_{\text{up}}$ between 20000 and 30000 K), which are suitable for evaluating the local electronic temperature. Of these, just four lines coming from the term a$^4$P (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 32000 K, well above the level #16 (less than 20000 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-redshifted ratios with the 1.257 μm line, integrated over the area where the a$^4$P 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 10000 to 20000 K. First, we note that, while at $T_e \lesssim 10000$ K the inclusion of three further levels does not change the results of the 16 level code, and strong differences emerge at higher temperatures (i.e. the ratio 1.257/1.749 decreases by about 70% at $T_e = 20000$ K). Second, ratios with the 1.814 μm, 1.967 μm, and 2.161 μm lines agree well with $T_e \sim 16000−17000$ K (the latter line has been de-blended from the fundamental line of [TiII], 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 $T_e \sim 8000$ 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

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$^2$ As we will see in the following, we estimate $T_e \sim 16000$ 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 $T_e = 10000$ K. This implies a very marginal increase in $n_e$.
Table 1. continued.

| Line id. | $\lambda_{\text{vac}}$ (µm) | $E_{\text{up}}$ (K) | $S/N_{\text{max}}$ | Line id. | $\lambda_{\text{vac}}$ (µm) | $E_{\text{up}}$ (K) | $S/N_{\text{max}}$ | Line id. | $\lambda_{\text{vac}}$ (µm) | $E_{\text{up}}$ (K) | $S/N_{\text{max}}$ |
|----------|----------------------------|-------------------|-------------------|----------|----------------------------|-------------------|-------------------|----------|----------------------------|-------------------|-------------------|
| 4–2S(0)$^{15}$ | 1.3425 | 22.354 | 9 | 4–2S(8) | 1.1987 | 28.885 | 7 | 4–2O(4)$^{15}$ | 1.5635 | 23.234 | 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(5) | 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 | 4–3S(3) | 2.1405 | 26.618 | 3 |
| 4–2S(7) | 1.2047 | 27.708 | 10 | 4–2O(3) | 1.5099 | 22.081 | 6 | 4–2O(2) | 1.4731 | 26.618 | 2 |
| 5–3S(3) | 1.3472 | 28.500 | 4 | 5–3Q(1) | 1.4929 | 26.737 | 3 | 5–3Q(7)$^{15}$ | 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 |
| 6–4S(1)$^{3}$ | 1.5015 | 31.664 | 5 | 6–4Q(7)$^{3}$ | 1.6829 | 34.175 | 5 | 6–4O(4)$^{21}$ | 1.7965 | 31.306 | 8 |
| 6–4Q(3)$^{3}$ | 1.6162 | 31.664 | 3 | 6–4Q(9)$^{3,20}$ | 1.7369 | 35.992 | 6 | 6–4O(4)$^{21}$ | 1.7965 | 31.306 | 8 |
| 7–5Q(5)$^{3}$ | 1.7784 | 36.591 | 3 | 7–5Q(7)$^{3}$ | 1.8765 | 38.912 | 6 | 7–5O(9)$^{32}$ | 1.9892 | 38.912 | 6 |

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] $^a\lambda_{\text{vac}}$H$_{1/2}^a$–$^a\lambda_{\text{vac}}$D$_{1/2}^a$;
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 H 4–9;
7 blends with 3–1O(9);
8 blends with 6–4Q(9), H4–10;
9 blends with 6–4O(4);
10 blends with 4–2S(3);
11 blends with 2–1S(9);
12 blends with 2–QO(9);
13 blends with 4–2O(1);
14 blends with [Fe II]$^a\lambda_{\text{vac}}$D$_{1/2}^a$–$^a\lambda_{\text{vac}}$Fe$_{1/2}^a$;
15 blends with 3–1Q(5);
16 blends with 3–1S(0);
17 blends with 2–OO(2);
18 blends with 5–3Q(7);
19 blends with 4–2O(4);
20 blends with 2–1S(13), H 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 $x$(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 $x$(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 ($\delta_{\text{Fe}}$) 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

$$\frac{x(\text{Fe})}{x(\text{P})} \approx 2 \times \frac{I([\text{Fe} \text{ II}].1.257)}{I([\text{P} \text{ II}].1.188)} \approx \frac{I([\text{Fe} \text{ II}].1.257)}{I([\text{P} \text{ II}].1.147)}.$$ (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 $\delta_{\text{Fe}} \simeq 0.20$, a condition verified in our case even in the bow flanks.

3.2. H$_2$ analysis

3.2.1. Extinction map

Looking at the line images of Fig. 1, it is evident that the bulk of the H$_2$ 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.

| Line id.          | $\lambda_{\text{vac}}$ (nm) | $E_{\text{up}}$ (K) | S/N max | Line id.          | $\lambda_{\text{vac}}$ (nm) | $E_{\text{up}}$ (K) | S/N max |
|-------------------|-------------------------------|---------------------|---------|-------------------|-------------------------------|---------------------|---------|
| [Fe II] lines      |                               |                     |         |                   |                               |                     |         |
| a$_D$7/2$\rightarrow$a$_D$3/2 | 1.2570                        | 11 446              | 700     | a$_D$7/2$\rightarrow$a$_D$3/2 | 1.2682                        | 11 446              | 1.8179  |
| a$_D$7/2$\rightarrow$a$_D$5/2 | 1.3209                        | 11 446              | 130     | a$_D$7/2$\rightarrow$a$_D$5/2 | 1.2707                        | 11 446              | 1.8179  |
| a$_D$7/2$\rightarrow$a$_F$3/2 | 1.9541                        | 11 446              | 7       | a$_D$7/2$\rightarrow$a$_F$3/2 | 1.6642                        | 11 446              | 1.8179  |
| a$_D$7/2$\rightarrow$a$_F$9/2 | 1.6440                        | 11 446              | 720     | a$_D$7/2$\rightarrow$a$_F$9/2 | 1.7454                        | 11 446              | 1.8179  |
| a$_D$7/2$\rightarrow$a$_D$5/2 | 1.8009                        | 11 446              | 99      | a$_D$7/2$\rightarrow$a$_D$5/2 | 1.9675                        | 11 446              | 1.8179  |
| a$_D$9/2$\rightarrow$a$_D$7/2 | 1.1916                        | 12 074              | 7       | a$_D$9/2$\rightarrow$a$_D$7/2 | 2.1609                        | 12 074              | 1.8179  |
| a$_D$9/2$\rightarrow$a$_D$7/2 | 1.2489                        | 12 074              | 17      | a$_D$9/2$\rightarrow$a$_D$7/2 | 1.7489                        | 12 074              | 1.8179  |
| a$_D$9/2$\rightarrow$a$_D$7/2 | 1.2946                        | 12 074              | 70      | a$_D$9/2$\rightarrow$a$_D$7/2 | 1.8139                        | 12 074              | 1.8179  |
| a$_D$9/2$\rightarrow$a$_D$7/2 | 1.3281                        | 12 074              | 42      | a$_D$9/2$\rightarrow$a$_D$7/2 | 1.2675                        | 12 074              | 1.8179  |
| a$_D$9/2$\rightarrow$a$_D$7/2 | 1.5339                        | 12 074              | 30      | a$_D$9/2$\rightarrow$a$_D$7/2 | 1.1885                        | 12 074              | 1.8179  |
| a$_D$9/2$\rightarrow$a$_F$3/2 | 1.6773                        | 12 074              | 157     | a$_D$9/2$\rightarrow$a$_F$3/2 | 2.0466                        | 12 074              | 1.8179  |
| a$_D$9/2$\rightarrow$a$_F$3/2 | 1.8005                        | 12 074              | 35      | a$_D$9/2$\rightarrow$a$_F$3/2 | 2.1334                        | 12 074              | 1.8179  |
| a$_D$9/2$\rightarrow$a$_D$7/2 | 1.2791                        | 12 489              | 41      | a$_D$9/2$\rightarrow$a$_D$7/2 | 2.2442                        | 12 489              | 1.8179  |
| a$_D$9/2$\rightarrow$a$_D$7/2 | 1.2981                        | 12 489              | 35      | a$_D$9/2$\rightarrow$a$_D$7/2 | 2.2444                        | 12 489              | 1.8179  |
| a$_D$9/2$\rightarrow$a$_F$3/2 | 1.5999                        | 12 489              | 46      | a$_D$9/2$\rightarrow$a$_F$3/2 | 2.0157                        | 12 489              | 1.8179  |
| a$_D$9/2$\rightarrow$a$_F$3/2 | 1.7116                        | 12 489              | 13      | a$_D$9/2$\rightarrow$a$_F$3/2 | 2.2541                        | 12 489              | 1.8179  |
| a$_D$9/2$\rightarrow$a$_F$3/2 | 1.7976                        | 12 489              | 36      | a$_D$9/2$\rightarrow$a$_F$3/2 | 1.1446                        | 12 489              | 1.8179  |
| H lines           |                               |                     |         | Other lines       |                               |                     |         |
| 3–5 (Paβ)         | 1.2822                        | 151 492             | 21      | He i $^1$P$_1$$^1$S$_0$ | 2.0587                        | 246 226             | 3       |
| 4–14              | 1.5884                        | 156 999             | 3       | He i $^1$D$_1$–$^1$P$_1$ | 2.6067                        | 282 101             | 8       |
| 4–13              | 1.6114                        | 156 870             | 4       | He i $^1$P$_0$–$^3$P$_0$ | 1.9522                        | 289 992             | 5       |
| 4–12              | 1.6412                        | 156 708             | 3       | [P II] $^1$D$_2$–$^1$P$_1$ | 1.1471                        | 12 764             | 5       |
|                   |                               |                     |         | [P II] $^3$D$_2$–$^3$P$_1$ | 1.8686                        | 12 764             | 16      |
|                   |                               |                     |         | [Co II] $^3$F$_{4}$–$^3$P$_{5}$ | 1.5474                        | 14 119             | 5       |

Notes: * 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). $^a$ Lines coming from the same upper level are grouped, and the first term of each group is evidenced with bold-face characters.

H$_2$ emission. Therefore, as a first step in the H$_2$ 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 $\mu$m 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 AV map constructed from [Fe II] lines, with a partial spatial overlap in the areas corresponding to knots B3 and B1 of D99. The AV 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 AV 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; Gianninni et al. 2004) and in HH99B itself (MC04), where the extinction computed from [Fe II] lines is systematically higher than probed with H$_2$ lines. This may stem from the extinction being in these cases computed from the 1.257 $\mu$m/1.644 $\mu$m 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. Grebel 1994), plotting ln(N$_{J}/g_J$) against E$_{J}/k$. Here N$_{J}$ (cm$^{-2}$) is the column density of the level (J, $E_{J}$ (K) its excitation energy, and g$_{J}$ = (2J+1)(2J+1) the statistical weight (here we assume that I = 0, 1 for para- and ortho-H$_2$). If the gas is thermalised at a single temperature, the
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 ≥ 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 $P_{\alpha}/Br_\gamma$ 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’Cooey 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 $\approx$2000 K up to 6000 K occurs from the receding parts of the shock towards the head. We underline that this gradient can be traced because of the very large number of H$_2$ lines detected, which cover the Boltzmann diagram up to excitation energies of $\approx$38 000 K, therefore sensitively widening the dynamical range of temperatures typically probed with H$_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 $T \approx 5000$ K) at the bow head (hence the contours here give the gas 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 reforming 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. $\frac{[I_{1.257}/I_{\lambda}]}{[I_{1.257}/I_{\lambda}]_{\text{mod}}}$ 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.

Fig. 10. Map of the percentage of iron in gas phase overlaid with the intensity contours of the [Fe II] 1.257 µm 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 Pa$\beta$ line. The S/N ratio of these lines, except for Br$\gamma$ and Pa$\beta$, is so low, however, that detailed modelling is prohibitive. Thus, we used only the Pa$\beta$/Br$\gamma$ ratio to independently estimate the extinction. Assuming case B recombination (Storey & Hummer 1995), we obtain $A_V = 1.8 \pm 1.9$ mag.

More interesting parameters, i.e. the hydrogen fractional ionisation $x_e$ and the hydrogen post-shock density $n_H = n_e/x_e$, are obtainable from the observed intensity ratio [Fe II] 1.257/Pa$\beta$. As
described in detail in Nisini et al. (2002), under the assumption that iron is singly ionised, such a ratio can be expressed as

\[ x_e = \delta_{Fe}(\text{Fe/H})_0 \left( \frac{[\text{Fe} \, \text{II} \, 1.257]}{\text{Pa} \beta} \right)^{-1} \frac{\epsilon_{[\text{Fe} \, \text{II} \, 1.257]}}{\epsilon_{\text{Pa} \beta}} \]  \tag{2}

with \( \delta_{Fe} \) the gas-phase iron fraction with respect to the solar Fe abundance \((\text{Fe/H})_0\) and \(\epsilon_{[\text{Fe} \, \text{II} \, 1.257]}\) and \(\epsilon_{\text{Pa} \beta}\) (in erg cm\(^3\) s\(^{-1}\)) the emissivities of the two lines, taking \(\epsilon_{\text{Pa} \beta}\) from Storey & Hummer (1995). This quantity was computed for the physical conditions derived at the bow head, i.e. \(T = 16000\, \text{K}, n_e = 6 \times 10^3\, \text{cm}^{-3}, \delta_{Fe} \sim 0.7\), having taken \((\text{Fe/H})_0 = 2.8 \times 10^{-5}\) (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 \(T_e \leq 10000\, \text{K}, a\) 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 & Eisloeffel 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 report 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 (\(\epsilon_{\text{peak}}, \text{FWHM}\)). 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 \(\epsilon_{\text{peak}}\) 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 \(FHWM_{\text{obs}}\) is 85–105 \(\text{km s}^{-1}\), that, deconvolved with the instrumental profile, measured on atmospheric OH lines, roughly gives an intrinsic line width of \(\sim 20–40\, \text{km s}^{-1}\). 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 \(FHWM_{\text{obs}}\) 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 \(\sim 70\, \text{km s}^{-1}\).
Fig. 13. Local standard of rest (LSR) velocity map of the 2.122 μm line peak, with superimposed line intensity contours. We indicate with a white line the diameter 2Rdis of the last cap beyond which the bulk of H2 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 (∼80 km s⁻¹) at which H2 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. [FeII]

We performed the kinematical analysis of the ionic gas component on the two brightest [Fe II] lines at 1.257 and 1.644 μm. 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 vbow = 115 ± 5 km s⁻¹, which agrees with the prediction by D99 (80–120 km s⁻¹) derived from the overall shape of the bow and the characteristics of the H2 2.122 μm line profile.

In Fig. 14 we show the radial velocity map of the 1.644 μm 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 α ≠ 0°, 180°, 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 H2 breakdown velocity (vdis), 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 (∼45°) inferred by D99 for a range of vdis between 70 and 90 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 km s⁻¹ was inferred by Kwan (1977), subsequently Draine et al. (1983) found vdis = 50 km s⁻¹, a result confirmed by Smith & Brand (1990) and Smith (1991). More recently, Le Bourlot et al. (2002) have shown that vdis can increase up to 80 km s⁻¹ for values of the pre-shock density around 10³ cm⁻³. Our measurement therefore agrees with the last prediction. Moreover, vdis ∼ 80 km s⁻¹ is consistent with the FWHM of the 2.122 μm 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 ro-vibrational H2 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.
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 ($E_{up} \gtrsim 30 000$ 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 $\sim 16\ 000$ K at the apex to less than $10\ 000$ 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 $\sim 0.6$ and a post-shock density of $\sim 10^4$ 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 $T \sim 6000$ 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 towards knot B0. Both these circumstances are not accounted for by models that have attempted to interpret the H$_2$
angle around the $z$-axis, $\theta$ the angle between the bow direction and the tangent to the parabolic surface, and $\alpha$ 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

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

where $z_{\text{max}}$ 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 $z_{\text{dis}}$ the position along the $z$-axis where the leading edge plane is located. Certainly it depends on the shock velocity at the bow apex, $v_{\text{bow}}$, on the $H_2$ breakdown velocity, $v_{\text{dis}}$, 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 $\theta$, $\tan \theta = dR/dz$:

$$v_{\text{dis}} = v_{\text{bow}} \frac{dR/dz}{\sqrt{1 + (dR/dz)^2}}.$$  \quad (A.2)

Substituting the parabolic equation in this formula, we get

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

and

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

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

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

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

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

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

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

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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, $\phi$ the azimuthal 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 Bourlot et al. (2002) of $v_{\text{dis}}$ 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 $v_{\text{shock}}$ = 50 km s$^{-1}$ contrasts with our measure of $v_{\text{shock}}$ = 110–120 km s$^{-1}$. Thus, the modelling of the [Fe II] emission may have to be revised
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