Quantitative optical and near-infrared spectroscopy of H$_2$ towards HH91A

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ABSTRACT

Aims. Optical and near-infrared spectroscopy of molecular hydrogen in interstellar shocks provide a very powerful probe to the physical conditions that prevail in interstellar shocks.

Methods. Integral-field spectroscopy of H$_2$ in the optical wavelength region and complementary long-slit near-infrared spectroscopy towards HH91A is used to characterize the ro-vibrational population distribution among H$_2$ levels with excitation energies up to 30 000 cm$^{-1}$.

Results. The detection of some 200 ro-vibrational lines of molecular hydrogen ranging between 7700 Å and 2.3 μm is reported. Emission lines which arise from vibrational levels up to $\nu' = 8$ are detected. The H$_2$ emission arises from thermally excited gas where the bulk of the material is at a temperature of 2750 K and where 1% is at 6000 K. The total column density of shocked molecular hydrogen is $N$(H$_2$) = $10^{18}$ cm$^{-2}$; Non-thermal excitation scenarios such as UV fluorescence do not contribute to the H$_2$ excitation observed towards HH91A.

Conclusions. The emission of molecular hydrogen towards HH91A is explained in terms of a slow J-shock which propagates into a low-density medium which has been swept-up by previous episodes of outflows which have occurred in the evolved HH90/91 complex.

Key words. ISM: individual objects: HH91A - ISM: Herbig-Haro objects - ISM: jets and outflows

1. Introduction

The study of molecular hydrogen emission lines in star-forming regions provides a powerful tool to gain insight into the physical processes which occur during the early stages of star formation. Outflows from young stellar objects drive powerful shock waves into the interstellar medium. The heating associated with the shocks can give rise to the excitation and dissociation of H$_2$. For low-mass protostars, the total H$_2$ luminosities are proportional to the accretion rates during the early phases of the protostellar evolution, and evidence exists that the proportionality extents to the high-mass stellar regime as well (Froebrich et al. 2003, Davis et al. 2004, Caratti o Garatti et al. 2006, Gredel 2006). These findings support a scenario where high-mass star formation proceeds via accretion as well but at significantly larger accretion rates, compared to their low-mass counterparts (e.g. McKee & Tan 2003, Yorke & Sonnenhalter 2002). The shock waves that lead to H$_2$ emission are either continuous (C-shock) or jump type (J-shock), depending on the physical conditions in the pre-shock gas, such as the magnetic field strength and the degree of ionization. The physical parameters and the H$_2$ luminosities depend on the evolutionary state of the driving source. For instance, jets from Class 0 sources travel in the high density gas from which the protostars are forming, and strong H$_2$ emission from C-type shocks is expected. Jets from older protostars propagate into a medium at lower density, since the mass loss during the early phase of the protostellar evolution has already swept up much of the ambient gas - conditions which favor dissociative J-type shocks (Caratti o Garatti et al. 2006). The C-type shocks produce a large column of warm gas in the $\nu'$=0 levels of H$_2$, while the J-type shocks produce large columns of hot gas of several 1000 K in the higher vibrational levels (Cabrit et al. 2004, Smith, O’Connell & Davis (2007), and references therein).

Comprehensive near-infrared spectroscopy of molecular hydrogen emission in Herbig-Haro (HH) objects covering the J-, H-, and Ks-bands have consequently been used to probe the physical conditions in molecular outflows from protostars (e.g. Caratti o Garatti et al. 2006, and references therein). The H$_2$ emission in Herbig-Haro objects is in general dominated by thermal emission which arise from rotational levels in $\nu'$=1–5. In general, J-type shocks are preferred to explain the observed H$_2$ emission (Smith 1994; Gredel 1994, 1996; McCoey et al. 2004, Nisini et al. 2002 among others), yet it has been noted that the population distribution among ro-vibrational levels in $\nu'$=1–5 is not the best discriminator to unambiguously infer the type of shock that is at work (Flower et al. 2003). Using emission from pure rotational lines in the (0,0) band of H$_2$, Giannini et al. (2006) convincingly demonstrated that the emission towards HH54 arises from a steady-state J-shock.

In the following sections, a quantitative study of the molecular hydrogen emission in HH91A is presented. The novel aspect of the present study is given by the study of H$_2$ emission lines in the optical wavelength region between 7700–8700 Å, and the study of relatively faint emission lines which arise from very high-excitation ro-vibrational levels in the near-infrared.
HH91A is part of the HH90/91 complex of Herbig-Haro (HH) objects which is located in the L1630 cloud. A comprehensive optical/infrared/millimeter study has been performed by Grede, Reipurth & Heathcote (1992). Complementary near-infrared observations were presented by Davis et al. (1994). The complex shows widespread and diffuse emission of molecular hydrogen which extends over several square arcmin. Superimposed are a number of very bright H$_2$ knots such as HH91A. The bulk of the H$_2$ emission from HH91A arises from hot gas at a temperature of 2750 K (Grede et al. 1992). Deep near-infrared imaging by Monetti & Reipurth (1995) did not detect the energy source that drives the HH90/91 outflow. HH90/91 has been characterized to present a fairly evolved state of Herbig-Haro objects (Grede et al. 1992).

Because the H$_2$ emission towards HH91A is very bright indeed, HH91A affords the possibility to study emission from very high-excitation levels of H$_2$ which arise in the optical and near-infrared wavelength regions. The population density in these levels provides a very sensitive discriminator among the various physical processes that contribute to the excitation of H$_2$ in shocks. The optical spectra of HH91A obtained with the integral field spectrograph PMAS at the Calar Alto 3.5m telescope are described in Sect. 2, together with complementary near-infrared spectra obtained with SOFI at the ESO/La Silla New Technology Telescope. The results are summarized in Sect. 3, which also contains a description of a theoretical model of H$_2$ which is compared with the observations. We conclude with a discussion of the significance of non-thermal excitation scenarios of the H$_2$ emission towards HH91A in Sect. 4.

### 2. Observations and Reduction

Optical spectroscopy of HH91A was carried during the nights of Feb 15 and 16, 2004, using the Potsdam Multi-Aperture Spectrophotometer PMAS at the Calar Alto 3.5m telescope (Roth et al. 2005). PMAS is an integral field instrument and was used in its standard configuration with a 16 x 16 lenslet array of 8" x 8" on the sky. The R1200 reflective grating provided a spectral resolution of approximately R = λ/Δλ = 10,000. The grating was used at encoder settings of 49° and 46°, which resulted in a spectral coverage of 7690–8270 Å and 8400–8980 Å, respectively. Sky-subtraction was achieved using the nod-and-shuffle technique (Roth et al. 2004), where the charge-shuffle mode of the CCDs is used to perform beam-switching between HH91A and a sky position during ongoing integrations. This mode results in a very high degree in the accuracy of the sky subtraction. Atmospheric transmission was corrected via the observation of various telluric standard stars. The data were obtained during non-photometric observing conditions which did not allow to derive a flux calibration. However, a number of H$_2$ emission lines in the 7700–8700 Å optical spectra arise from the same upper ro-vibrational levels than emission lines in the near-infrared wavelength region. Examples are the (4,1) S(3) line near 8500 Å and the (4,2) S(3) and (4,2) Q(5) lines in the J-band which arise from ν$'$= 4, J$''$= 5, or the (3,0) S(3), (3,0) Q(5) in the optical and the (3,1) S(3) and (3,1) Q(5) lines, which arise from ν$'$=3, J$''$=5. The near-infrared observations were obtained during photometric conditions, and the H$_2$ population densities inferred from the near-infrared observations were used to obtain a relative flux calibration for the optical spectrum. We ignore reddening towards HH91A following Grede et al. (1992). The PMAS observations afford the possibility to study spatial variations in line ratios across the H$_2$ line emitting regions. The H$_2$ emission detected in the optical wavelength regime is very faint indeed. The spectra in a PMAS pixel (0.25 square arcseconds) have a too low signal to noise ratio to derive meaningful conclusions. We thus proceed and sum up all spectra over the central 5″ emission region and surrender on the potential of the PMAS observations to study changes in the H$_2$ excitation across HH91A.

The near-infrared spectra cover the J, H, and Ks-band atmospheric windows and were obtained during the nights of Dec 20 and 21, 2003, using SOFI at the La Silla New Technology Telescope NTT. The reduction of the data and the flux calibration follows recipes described elsewhere (e.g. Grede 2006). The observations were carried out during photometric conditions and thus allow to infer total column densities in the various ro-vibrational levels of H$_2$ (see Grede 2006 for details). The spectra were obtained using a slit width of 0″6. The blue grism GB in order 1 and the HR grism in orders 2 and 1 were used which provide spectral resolutions of R = 600, 1560, and 1800 in the J-, H-, and Ks-bands, respectively. The one-dimensional spectra were extracted using a 20-pixel extraction window along the slit (5″8), which corresponds to an ‘aperture’ of 3.6 square arcseconds or a solid angle of Ω = 9 × 10$^{-11}$ sr$^{-1}$.

### Table 1. Optical emission lines of H$_2$ detected with PMAS

| Line       | Wavelength (Å) | FluxF (×10$^{-19}$Wm$^{-2}$) | N(v′J') (10$^{15}$cm$^{-2}$) |
|------------|----------------|-------------------------------|-------------------------------|
| (3, 0)S( 8) | 7781           | 2.60(0.5)                     | 1.30(0.3)                     |
| (3, 0)S( 7) | 7784           | 8.10(0.8)                     | 3.90(0.4)                     |
| (7, 3)S( 9) | 7782           | ≤ 1                           | ≤ 0.1                         |
| (3, 0)S( 9) | 7793           | 6.9(0.7)                      | 3.2(0.6)                      |
| (3, 0)S( 6) | 7804           | 2.90(0.3)                     | 1.6(0.3)                      |
| (3, 0)S(10) | 7821           | ≤ 0.4                         | ≤ 0.2                         |
| (3, 0)S( 5) | 7840           | 8.10(0.8)                     | 4.9(1.0)                      |
| (3, 0)S(11) | 7865           | 3.0(0.3)                      | 1.5(0.3)                      |
| (3, 0)S( 4) | 7892           | 1.50(0.3)                     | 1.10(0.3)                     |
| (3, 0)S(12) | 7924           | ≤ 0.4                         | ≤ 0.2                         |
| (3, 0)S( 3) | 7962           | 5.8(0.6)                      | 4.9(1.0)                      |
| (7, 3)S(11) | 7978           | ≤ 0.4                         | ≤ 0.1                         |
| (3, 0)S(13) | 7999           | 0.9(0.3)                      | 0.6(0.2)                      |
| (3, 0)S( 2) | 8049           | 1.0(0.3)                      | 1.1(0.4)                      |
| (3, 0)S(14) | 8090           | ≤ 0.4                         | ≤ 0.3                         |
| (3, 0)S( 1) | 8153           | 2.30(0.3)                     | 3.6(0.7)                      |
| (4, 1)S( 4) | 8390           | 2.8(0.3)                      | 0.7(0.1)                      |
| (4, 1)S(11) | 8398           | 4.1(0.4)                      | 0.8(0.2)                      |
| (4, 1)S( 3) | 8462           | 5.9(0.6)                      | 1.6(0.3)                      |
| (4, 1)S(12) | 8471           | 1.0(0.3)                      | 0.2(0.0)                      |
| (8, 4)S( 9) | 8500           | ≤ 0.4                         | ≤ 0.2                         |
| (3, 0)Q( 1) | 8500           | 1.2(0.3)                      | 2.8(0.7)                      |
| (3, 0)Q( 2) | 8525           | ≤ 0.4                         | ≤ 1.3                         |
| (4, 1)S( 2) | 8552           | 1.4(0.3)                      | 0.5(0.1)                      |
| (3, 0)Q( 3) | 8563           | 3.3(0.3)                      | 11.4(2.3)                     |
| (4, 1)S(13) | 8562           | 3.3(0.3)                      | 0.8(0.2)                      |
| (4, 1)S( 1) | 8662           | 2.5(0.3)                      | 1.3(0.3)                      |
| (4, 1)S(14) | 8673           | 1.5(0.3)                      | 0.4(0.1)                      |
| (3, 0)Q( 5) | 8677           | 1.5(0.3)                      | 5.4(1.1)                      |
| (3, 0)Q( 4) | 8613           | ≤ 0.4                         | ≤ 1.4                         |
| (3, 0)Q( 2) | 8750           | ≤ 0.6                         | ≤ 1.2                         |
| (3, 0)Q( 6) | 8753           | ≤ 0.6                         | ≤ 2.3                         |
| (8, 4)S(11) | 8763           | ≤ 0.6                         | ≤ 0.1                         |
| (4, 1)S( 0) | 8792           | ≤ 0.6                         | ≤ 0.5                         |
| (4, 1)S(15) | 8803           | ≤ 0.6                         | ≤ 0.2                         |
3. Results

3.1. Optical spectroscopy using PMAS

The optical spectra obtained towards HH91A are shown in Figs. 1[2]. Emission from the (3,0) S(11)–S(14) lines is detected long-ward of the (3,0) S(8) line at 7781 Å (Fig. 1). The (3,0) Q(1)–Q(6) lines are detected as well, together with several lines in the (4,1) S-branch (Fig 2). The (8,4) S(9) line near 8496 Å is clearly detected. A wavelet analysis of the optical spectra confirms the marginal detection of the (7,3) S(11) line at 7978 Å, and of the (8,4) S(11) line near 8763 Å. The signal to noise ratio in the latter two lines is very low indeed, and as a standalone result, the claim of the detection of the latter three emission lines in our spectra may be disputed. The red lines in Figs. 1 and 2 reproduce the expected fluxes in the (7,3) S(11) and (8,4) S(9) and S(11) lines from a model which is presented in detail below. The model is based on the analysis of the full set of some 200 observed H$_2$ emission lines towards HH91A and substantiates the result from the wavelet analysis, which indicates that emission from the (7,3) and (8,4) bands towards HH91A is detected.

3.2. Near-infrared spectroscopy using SOFI

The near-infrared spectra obtained with SOFI are reproduced in Figs. 3[17]. The J-band spectra shown in Figs. 3[4] are dominated by emission from the (2,0) S-branch (band-head near 1.055 μm), the (3,1) S-branch (band-head near 1.118 μm), the (4,2) S-branch (band-head near 1.185 μm), and the (5,3) S-branch (band-head near 1.282 μm). Strong emission lines from the (2,0), (3,1), and (4,2) Q-branch are detected as well. In addition, various emission lines from the (6,3) S-branch band are detected long-ward of its band-head near 9506 Å, and from the (7,4) S-branch (band-head at 10028 Å), are detected (cf. Fig. 5). The inferred population densities in the ro-vibrational levels of v′=6 imply that emission in the (6,4) band occur at flux levels above the noise of the spectra presented here. The (6,4) Q(1)–Q(9) lines are clearly detected (see below). The expected emission lines in (6,4) S-branch, up to the band-head marked by the (6,4) S(8) line, near 13840 Å, is reproduced in Fig. 4 by the red line. The (6,4) S-branch is located in a region of poor atmospheric transmission between 1.35–1.5 μm, where the fluxes of the measured emission lines are highly uncertain. The modeled emission in the (6,4) S-branch is consistent with the observations. The emission feature near 9825–9851 Å corresponds to emission from atomic carbon (cf. Sect. 5). Emission from [FeII], which is generally observed in HH-objects, is absent.

The H-band spectra towards HH91A are shown in Figs. 5[6]. The H-band spectrum is dominated by strong emission from the (1,0) S-branch (band-head marked by (1,0) S(14) near 16296 Å) and relatively strong emission from the (3,1) O(5)–O(7), (4,2) Q(11)–Q(13). In addition, emission from (6,4) Q(1)–Q(9) is detected. The bold red line reproduced in Figs. 5[6] correspond to the theoretical emission from a model presented below.

Finally, the Ks-band spectrum is shown in Fig. 7. The emission is dominated by the very strong (1,0) S(0)–S(2) lines and the (2,1) S(1)–S(4) lines. Emission from (3,2) S(2)–S(5) and from (4,3) S(4) is detected as well. The strong H$_2$ lines such as the (1,0) S(7) and the (1,0) S(1) line show pronounced line wings. Those wings have no astrophysical significance and arise from an instrumental defect of SOFI, evidenced by the fact that these lines do not show wings in the spectra taken previously with IRSPEC (Gredel et al. 1992).

The spectra shown in Figs. 1[7] contain some 200 emission lines of molecular hydrogen. The inferred fluxes F of the various lines are given in column 3 of Tables 1 and 2 with flux uncertainties in parenthesis. The optical spectra have limiting line fluxes of about 0.5 × 10$^{-19}$ W m$^{-2}$, as judged from noise in the flux-scaled spectra (see above). Limiting fluxes are about 10$^{-19}$ W m$^{-2}$ in the H-band and 10$^{-19}$ W m$^{-2}$ in the Ks-band taken with grism HR. For the stronger lines, flux uncertainties introduced by the calibration of the atmospheric transmission are estimated to be of the order of 10–20% of the total line flux. Fluxes derived from emission lines which occur in spectral regions which are dominated by narrow, telluric absorption lines, such as the 13 500–15 000 Å region, are uncertain by larger amounts. Columns 1, 2, and 4 contain the line identification, the vacuum wavelength λ, and the inferred column density N(v′J′) of the corresponding upper ro-vibrational level v′J′, respectively. Numbers in parenthesis in column 4 of Tables 1 and 2 are uncertainties in column densities.

Because of the relatively low spatial resolution provided by SOFI, many of the features detected in the J-, H-, and Ks-bands are blends of two or more emission lines of H$_2$. In cases of line blends, no effort was made to de-convolve the lines or to assign fractional flux values to the individual components. Rather, the full line flux was assigned to each of the possible ro-vibrational lines which occur at the given wavelength. Examples are the (4,2) S(9) + S(10) blend near 1.196 μm, the (2,0) Q(2) + (4,2) S(4) blend near 1.242 μm, the (4,2) S(2) + (5,3) S(10) blend near 1.284 μm, or the (2,0) Q(7) + (5,3) S(7) blend near 1.288 μm. The entries in Table 1 are thus to be read with care - in cases where line blends occur, the listed H$_2$ column densities are too large by factors of a few. Unresolved line blends are explicitly identified in Figs. 1[7] and in Tables 1 and by an asterisk.

The H$_2$ column densities listed in Tables 1 and 2 are nevertheless used to construct the H$_2$ excitation diagram with values of ln(N(v′J′)/g) plotted versus excitation energy E(v′J′) (see eg. Gredel 2006 for details). The diagram is reproduced in Fig. 8. The occurrence of line blends introduces some scatter to the excitation diagram. The scatter has no physical origin nor is it introduced by non-thermal excitation scenarios. This statement is justified in detail in Sect. 4 below. We proceed in the following iterative way to derive the ro-vibrational excitation temperature of the v′J′ levels. The population densities in the H$_2$ levels up to an excitation energy of say 10$^3$ cm$^{-1}$ is consistent with an excitation temperature of 2750 K, which is the temperature derived by Gredel et al. 1992 from their IRSPEC spectra which were obtained at a higher spectral resolution than the spectra presented here. The population densities among the ro-vibrational levels above excitation energies of 10$^3$ cm$^{-1}$ deviate from the population densities expected for a thermalized distribution at 2750 K. The deviation causes a curvature in the excitation diagram and indicates that a fraction of 1% of the gas is at the very high temperature of 6000 K. This statement assumes that all the levels up to excitation energies of about 30 000 cm$^{-1}$, or some 40 000 K, are thermalized. Higher gas-kinetic temperatures are in principle possible if it is assumed that the levels are sub-thermally excited. The curvature in the H$_2$ excitation diagram is not very pronounced and is only established through the observation of high-excitation emission lines with excitation energies above 15 000 cm$^{-1}$. This is the reason why the curvature went unnoticed in the earlier work of Gredel et al. (1992). The relatively low degree of temperature stratification in HH91A, combined with the absence of emission from [FeII], supports the general finding of Caratti o Garatti et al. (2006) who concluded that a significant temper-
Fig. 1. Observed spectrum towards HH91A obtained with PMAS, with monochromatic fluxes plotted versus wavelength (in Å). The position of the (3,0) S(1)–S(14) lines are indicated. The (7,3) S(11) line near 7978 Å is marginally detected. A model spectrum with emission from vibrational levels $v' = 3$ and $7$ is color-coded in blue and red, respectively (cf. Sect. 4). The emission near 8727 Å arises from atomic carbon.

ture stratification in the $H_2$ emitting gas is in general observed in HH-objects which show [FeII] emission as well.

In order to judge whether the above conclusions are fully consistent with the observed optical and near-infrared spectra, we have modeled the spectrum expected from a two-component gas mixture with is at a temperature of 2750 K and where a fraction of 1% of the gas is at a temperature of 6000 K. We have used the models of Gredel & Dalgarno (1995) to calculate the theoretical $H_2$ emission spectrum. From the entry rates into the ro-vibrational levels $v'J'$ of the electronic ground state of $H_2$, a spectrum (Voigt profiles) is calculated as a function of parameters such as the total $H_2$ column density, the reddening $E_B - V$, the desired spectral resolution $R = \lambda/\Delta\lambda$, etc. We ignore reddening towards HH91A (cf. Gredel et al. 1992) and calculate the expected emission spectra for the various spectral resolutions in the PMAS and SOFI spectra. Apart from the relative flux calibration of the PMAS spectra as discussed above, the only scaling that we involve is introduced by a forced match of the predicted and calculated flux in the (1,0) S(1) line. For a gas mixture of warm molecular gas at 2750K plus a fraction of 1% at 6000 K, the model calculation produces a total $H_2$ flux of $F_{tot}(H_2) = \sum_{v'J'} F(v'J'v''J'') = 19.8 \times F(1301)$, where $F(1301)$ is the flux in the (1,0) S(1) line and where the summation is carried out over all possible emission lines of $H_2$. The total $H_2$ population density, for the two-component gas mixture adopted here, is $N_{tot}(H_2) = \sum_{v'J'} N(v'J') = 45.7 \times N(1,3)$, or $N_{tot}(H_2) = 1.26 \times 10^{18}$ cm$^{-2}$. The scaling factors (19.8 and 45.7 in the present case) are strongly dependent on the temperatures and column density ratios (cf. Gredel 1994).

The model calculations are reproduced by the colored lines in Figs. 1–7. In order to illustrate the contributions from the various vibrational levels of $H_2$, emission which arises from vibrational levels $v' \leq 3$ is color coded in blue, emission from $v' = 4$ in green, emission from $v' = 5$ in magenta, and emission from $v' \geq 6$ in red. The agreement of the modeled spectrum with the observations is excellent. In general, the line fluxes in the 200 or so observed emission lines of $H_2$ are reproduced within 20%. Relatively large deviations (factor of 2) between the model spectrum and the observations occur for the (3,0) S(1) line near 8150 Å, for (4,1) S(1) and (3,0) Q(5) near 8670 Å, and for (3,1) Q(7) near 1.37 μm, (3,1) O(5) near 1.523 μm, and (2,0) O(7) near 1.545 μm. The model also fails to reproduce the observed
Fig. 2. Observed spectrum towards HH91A obtained with PMAS, with monochromatic fluxes (in relative units) plotted versus wavelength (in Å). The position of various emission lines in the (3,0) and (4,1) bands are indicated. The (8,4) S(9) and (8,4) S(11) lines near 8500 Å and 8685 Å, respectively, are marginally detected. The emission which is color-coded in blue, green, and red corresponds to a model spectrum with emission from vibrational levels \( v' = 3, 4, \) and 8, respectively (cf. Sect. 4).

emission features near 1.03 µm but it does reproduce the (7,5) S-branch in the H-band, which contains lines which arise from the same upper ro-vibrational levels than the lines near the (7,4) S-branch band-head near 1.03 µm. This may indicate that emission other than from the (7,4) S-branch occurs near 1.03 µm. The model spectrum demonstrates that fluxes of a few \( 10^{-20} \) W m\(^{-2} \) of individual ro-vibrational lines in the (6,3), (6,4), (7,4), and (8,4) bands are expected from a thermally excited gas towards HH91A. Among the various high-excitation lines, the model reproduces perfectly well the band head of the (6,3) S-branch near 9500 Å, the (6,4) Q(1)–Q(9) lines in the H-band. Given that some of the discrepant lines occur in relatively poor atmospheric windows, and that the rest of the 200 or so observed lines are very well reproduced, and that fluxes among lines that arise from ro-vibrational levels that span excitation energies from 4000–30 000 cm\(^{-1} \) are accurately modeled, we ignore the discrepancies and conclude that the observed \( \text{H}_2 \) emission arises from thermal gas at 2750 K which contains a fraction of 1% at a temperature of 6000 K.

Tables 3 and 4 contain a full listing of our model results, and gives expected \( \text{H}_2 \) emission lines which have integrated line fluxes above \( F_{\text{tot}} = 10^{-19} \) W cm\(^{-2} \) (Table 3) and fluxes ranging between 0.5 – 1 \( \times 10^{-19} \) Wm\(^{-2} \) (Table 4). The predicted thermal fluxes towards HH91A from the two gas components (bulk at 2750 K and 1% at 6000 K) are listed separately in columns 4 and 5, respectively. The tables contain the line identification, the wavelength in µm, and the energy of the upper ro-vibrational level in cm\(^{-1} \), in columns 1–3, respectively. Total line fluxes are given in column 6. Figures 10-16 contain the residuals between the observed and the modeled \( \text{H}_2 \) line fluxes. As discussed earlier in Sect. 3, it can be seen that the overall agreement between the observed and the modeled spectra is excellent.

4. Discussion

Optical and near-infrared emission lines from molecular hydrogen which arise from very high-excitation ro-vibrational levels in the electronic ground state of \( \text{H}_2 \) are generally seen in sources where electronic states of \( \text{H}_2 \) are pumped in strong ultraviolet radiation fields, such as in NGC 2023 (McCartney et al. 1999). The absorption of ultraviolet radiation in the Lyman and Werner bands of \( \text{H}_2 \) and the subsequent decay of the excited...
Fig. 3. J-band spectrum towards HH91A obtained with SOFI. Plotted are monochromatic fluxes in units of $10^{-17}$ W m$^{-2}$ µm$^{-1}$ vs. wavelength in units of Å. The spectrum is dominated by strong emission lines which arise from the (2,0), (3,1), and (4,2) S-branches. Faint emission from various lines in the (6,3) and (7,4) S-bands is detected. The position of the various lines in the (6,3) S-branch between 9500–10 000 Å are indicated. The position of several lines converging to the band-head of the (7,4) S-branch between 10 030–10 050 Å are indicated as well. The emission near at 9825Å and 9851 Å arises from the $^1D_2 - ^3P_1$ and $^1D_2 - ^3P_2$ transition of [Cl]. The theoretical H$_2$ emission spectrum is reproduced in color, with emission from $v'=2$ and 3 in blue, from $v'=4$ in green, and from $v'=6$ and 7 in red.

electronic states via dipole radiation populates the ro-vibrational levels $v'J'$ of the electronic $X^1\Sigma^+_g$ ground state of H$_2$. The excited $v'J'$ levels cascade to lower ro-vibrational levels $v''J''$ via electric quadrupole (E2) radiation and give rise to optical and near-infrared emission of H$_2$. In regions with strong X-ray radiation fields, electronic states of H$_2$ may also be collisionally excited by energetic secondary electrons produced by X-ray ionizations (Gredel & Dalgarno 1995). X-rays have been detected in very fast shocks in HH-objects (HH2A, Pravdo et al. 2001; HH 154, Bally, Feigelson, & Reipurth 2003). Pumping by Ly$\alpha$ photons of H$_2$ is possible in a warm gas which contains a fraction of H$_2$ in the $v'=2,J'=5$ level (Schwartz et al. 1987). The excitation of electronic states by UV or Ly$\alpha$ photons follows dipole selection rules while the collisional excitation by secondary electrons does not. Non-thermal excitation of the ro-vibrational levels may also occur in a gas where H$_2$ reforms after the passage of a strong, dissociative shock (LeBourlot et al. 1995; Casu & Cecchi-Pestellini 2003, Tiné et al. 2003). In such models, uncertainties about whether the H$_2$ formation energy is equipartitioned among the ro-vibrational levels, the kinetic energy of the molecule, and the internal energy of the grain lattice, translate to significant differences in the modeled H$_2$ spectra, and renders a comparison with the observations difficult.

The shocked gas in molecular outflows from protostars may be affected by the non-thermal excitation scenarios described above. Fast, dissociative shocks produce a radiative precursor which contains a strong ultraviolet radiation field. Embedded TTau stars in the star forming regions may contribute a significant X-ray radiation field to the environment (Guedel et al. 2007, and references therein). Non-thermal excitation scenarios introduce a pronounced dependence of the rotational and vibrational excitation temperatures of the ro-vibrational levels in the electronic ground state of H$_2$. Such is evidenced by strong deviations from the smooth Boltzmann distribution which characterizes thermal gas.
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Fig. 4. J-band spectrum towards HH91A, with monochromatic fluxes in units of $10^{-17}$ W m$^{-2}$ µm$^{-1}$ vs. wavelength in units of Å. The strong emission lines which arise from the (2,0), (3,1), (4,2), and (5,3) bands are identified. The expected position and strength of modeled emission from the (6,4) S(3)–S(8) lines is indicated as well (cf. Sect. 4). The theoretical H$_2$ emission spectrum is reproduced in color, see Fig. 3 for details.

None of these effects dominate the excitation of H$_2$ in HH91A. What is immediately clear from the H$_2$ excitation diagram shown in Fig. 8, but more convincingly from the excellent agreement of the model H$_2$ emission spectra which arises from thermally excited gas and the observations, is that all ro-vibrational levels up to excitation energies of 40 000 K are in LTE. The fluxes in the high-excitation emission lines in the observed (6,4), (7,4), and (8,4) bands are in excellent agreement with the expected strengths from the two-component thermal gas described above. The presence of these lines does not require to employ non-thermal excitation scenarios to explain the observed H$_2$ emission towards HH91A.

At kinetic temperatures of a few 1000 K, the rate coefficients for collisional excitation of H$_2$ by hydrogen atoms are of the order of $10^{-12}$ cm$^{-3}$ s$^{-1}$. In order to estimate the extent at which the non-thermal excitation scenarios discussed above contribute to the H$_2$ excitation, we use the models of Gredel & Dalgarno (1995) to calculate the entry rates into the ro-vibrational levels of the ground state from X-ray and UV-fluorescence. X-ray ionization rates need to be significantly larger than $\zeta = 10^{-15}$ s$^{-1}$ for collisional impact excitations of electronic H$_2$ states by fast secondary electrons to result in entry rates which exceed those from thermal excitations in a gas of a few 1000 K temperature. The generally adopted value of the cosmic-ray ionization rate in dense gas is $\zeta = 10^{-17}$ s$^{-1}$. The upper limit to the ionization fraction from X-rays is about $x_e \leq 10^{-4}$. It can thus be ruled out that X-rays contribute significantly to the H$_2$ emission observed towards HH91A. Similarly, a strong ultraviolet radiation field which exceeds the strength of the ambient interstellar radiation field by factors of several 100 is required for UV fluorescence to compete with the thermal population of H$_2$ levels in the ground state. The presence of a fast, dissociative shock with a strong UV precursor should thus be ruled out as well towards HH91A.

The fact the H$_2$ levels up to excitation energies of 30 000 cm$^{-1}$ are thermalized requires very large densities in the compressed, post-shock gas. The critical densities which are required to populate the ro-vibrational levels are equal to the Einstein A-values divided by the collisional de-excitation rate coefficients, $n_{\text{crit}}(v\ J) = A(v\ J'v'J')/\langle \sigma v \rangle$. The critical densities exceed values of $n_{\text{crit}} > 10^7$ cm$^{-3}$ for levels with excitation energies above 30 000 cm$^{-1}$. A more careful inspection of the H$_2$ excitation diagram shown in Fig. 8 shows that the population density among
Fig. 5. H-band spectrum towards HH91A, with monochromatic fluxes in units of $10^{-17} \text{W m}^{-2} \mu\text{m}^{-1}$ vs. wavelength in units of Å. The emission lines reproduced in color correspond to a model calculation which is presented in Sect. 4. Emission from $v' = 1, 2, 3$ in blue, $v' = 4$ in green, $v' = 5$ in magenta, and $v' = 6$ and 7 in red. It is noted that emission from [FeII] $\lambda\lambda 16440, 16442$ near 16440 Å is absent.

some of the very high-excitation levels, with excitation energies above 30 000 K, may show signs of sub-thermal excitation. In particular, the population density inferred from the optical $(7,3) S(11)$ line at 7978 Å, which has an excitation energy of $30 368 \text{cm}^{-1}$, has a measured flux which is about a factor of three lower than what is expected from our two-component thermal model. This may indicate the onset of subthermal excitation for the very high levels such as the $v' = 7, J' = 13$ level from which the $(7,3) S(11)$ line arises.

From the optical observations of [SII] 6717Å and 6731Å lines, Gredel et al. (1995) inferred very low electron densities of the order of $n_e \approx 300 \text{ cm}^{-3}$ towards HH91A. This finding is consistent with the upper limit of the ionization fraction of $10^{-4}$ and the critical densities derived above. The absence of emission from [FeII] (e.g. the $\sigma^4 D_{7/2} - \sigma^4 F_{9/2}$ near 1.644μm) supports the idea that H$_2$ is excited by a relatively slow, non-dissociative shock. Emission from ionized atomic species such as [FeII] is often observed in Herbig-Haro objects (eg. Nisini et al. 2002), yet the strength of the atomic lines is not well reproduced by shock-models which explain the H$_2$ emission. This suggests that [FeII] arises from faster, dissociative shocks and in regions which are distinct from H$_2$-emitting regions. Weak emission from [CI] is seen near 8727 Å, with a flux of $F_{8727} \approx 0.8 \times 10^{-19} \text{ W m}^{-2}$, and near 9825 Å and 9851 Å of $F_{9825} = 10.8 \times 10^{-19} \text{ W m}^{-2}$ and $F_{9851} = 37 \times 10^{-19} \text{ W m}^{-2}$. The observed [CI]8727/(9825+9851) line ratio of 0.02 is well reproduced by slow, non-dissociative shocks. We thus conclude that the emission seen towards HH91A is produced in a slow J-type shock. This picture is in agreement with the expectations that evolved outflows favor the formation of J-shocks (Caratti o Garatti 2006). It has been pointed out by Flower et al. (2003) that the discrimination between C-type and J-type shocks based on H$_2$ excitation diagrams is far from straightforward. A J-shock is preferred here because C-type shocks fail, in general, to produce the high degree of thermalization that is observed here. This conclusion is in agreement with earlier results by Smith (1994) whose analysis is based on fewer observed H$_2$ lines.

As far as the possibility is concerned that the observed H$_2$ emission arises from molecules which reform after the passage of a fast, dissociative shock, firm statements are more difficult to reach. The H$_2$ emissivities produced from reforming H$_2$ in diffuse and dense gas were calculated by Tiné et al. (2003) and by
LeBourlot et al. (2002), Tiné et al. (2003) calculated an emission spectrum of H$_2$ produced via an Eley-Rideal process on graphite. In Fig. 9 we reproduce the H$_2$ emission spectrum which results from our two-component gas model (2750 K + 1% 6000 K). For the sake of simplicity, the width of the H$_2$ emission lines is kept constant at 200 Å over the spectral range of 5000 Å to 5 µm of Fig. 9. A comparison with Figs. 2 and 3 of Tiné et al. (2003) does not allow us to rule out the presence of re-forming H$_2$ molecules in HH91A nor does it support the idea that reformation occurs. In particular, the very strong emission in the (0,0) S(9) line predicted by Tiné et al. (2003) in their mechanism is expected from thermal gas at 2750 K as well. The models presented by Casu & Cecchi-Pestellini (2005) predict very large column densities in very high rotational levels (J > 20) of H$_2$. The wavelengths of the very high rotational lines are not covered by our observations.

5. Conclusions

The findings presented here are summarized as follows:

1. From the analysis of some 200 emission lines of molecular hydrogen which are detected towards HH91A, it is concluded that the emission arises from thermally excited H$_2$, where the bulk of the gas is at a temperature of 2750 K and where 1% of the gas is at a temperature of 6000 K. The total column density of the shocked H$_2$ is N(H$_2$) = 10$^{18}$ cm$^{-2}$.

2. Emission from very high-excitation lines in the (6,4), (6,3), (7,4), and (8,4) bands is detected, with excitation energies of the corresponding ro-vibrational levels of up to 40 000 K. The fluxes in these high-excitation lines are consistent with the expectations from a thermally excited gas.

3. It is suggested that the H$_2$ emission arises from a slow, non-dissociative J-shock. A comparison with model calculations shows that contributions from non-thermal excitation scenarios, such as H$_2$ pumping by Ly$\alpha$ or UV radiation, or collisional excitations by non-thermal, fast electrons, are not significant.

4. The results are inconclusive as far as the presence of H$_2$ emission from reforming molecules is concerned.

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Fig. 7. Ks-band spectrum towards HH91A obtained with SOFI, see caption of Fig. [5] for details. The wings in the (1,0) S(1) line arise from an instrumental defect of SOFI and have no astrophysical significance.
Fig. 9. Modeled H$_2$ emission spectrum which results from a total column of N(H$_2$) = 10$^{18}$ cm$^{-2}$ of hot gas at a temperature of 2750 K, which contains a fraction of 1% of hot gas at 6000 K. Fluxes are in units of 10$^{-19}$W m$^{-2}$ and wavelengths are in Å. Emission lines are Voigt line profiles at a FWHM of 200 Å.
Table 1. Near-infrared line detections obtained with SOFI

| Line        | Wavelength (Å) | Flux $P$ (10^{-19}Wm^{-2}) | $N(v'J')$ (10^{14}cm^{-2}) |
|-------------|----------------|-----------------------------|------------------------------|
| (6, 3)S(8)  | 0.953          | 4.7 (1.0)                   | 0.3 (0.1)                    |
| (6, 3)S(4)  | 0.959          | 1.7 (1.0)                   | 0.1 (0.0)                    |
| (6, 3)S(3)  | 0.966          | 4.1 (1.0)                   | 0.4 (0.1)                    |
| (6, 3)S(15)*| 1.040          | 5.0 (1.0)                   | 1.3 (0.3)                    |
| (2, 0)S(9)  | 1.054          | 75.8 (7.6)                  | 18.1 (3.6)                   |
| (2, 0)S(8)  | 1.058          | 23.0 (2.3)                  | 5.2 (1.0)                    |
| (2, 0)S(13) | 1.061          | 7.6 (1.0)                   | 3.2 (0.6)                    |
| (2, 0)S(7)  | 1.064          | 78.4 (7.8)                  | 17.3 (3.5)                   |
| (2, 0)S(6)  | 1.073          | 30.1 (3.0)                  | 6.7 (1.3)                    |
| (2, 0)S(15) | 1.078          | $\leq 1.2$                  | $\leq 0.9$                   |
| (2, 0)S(5)  | 1.085          | 106.9 (10.7)                | 24.8 (5.0)                   |
| (2, 0)S(4)  | 1.100          | 31.0 (3.1)                  | 7.8 (1.6)                    |
| Line       | Wavelength (Å) | Flux $F$ ($10^{-19}$Wm$^{-2}$) | $N$(v J) ($10^{14}$cm$^{-2}$) |
|-----------|---------------|-------------------------------|-------------------------------|
| (2, 0)S(3) | 1.117         | 60.4 (6.0)                    | 17.1 (3.4)                    |
| (3, 1)S(9)* | 1.120         | 29.7 (3.0)                    | 3.6 (0.7)                     |
| (3, 1)S(11)* | 1.121        | 29.7 (3.0)                    | 4.7 (0.9)                     |
| (3, 1)S(8)  | 1.124         | 13.2 (1.3)                    | 1.5 (0.3)                     |
| (3, 1)S(7)  | 1.130         | 36.5 (3.7)                    | 3.9 (0.8)                     |
| (3, 1)S(13) | 1.132         | 4.1 (1.0)                     | 1.0 (0.2)                     |
| (2, 0)S(2)  | 1.138         | 34.2 (3.4)                    | 11.4 (2.3)                    |
| (3, 1)S(6)  | 1.140         | 17.5 (1.7)                    | 1.8 (0.4)                     |
| (3, 1)S(5)  | 1.152         | 46.3 (4.6)                    | 5.0 (1.0)                     |
| (2, 0)S(1)  | 1.162         | 63.6 (6.4)                    | 27.2 (5.4)                    |
| (3, 1)S(4)  | 1.167         | 17.8 (1.8)                    | 2.0 (0.4)                     |
| (3, 1)S(3)  | 1.186         | 51.2 (5.1)                    | 6.4 (1.3)                     |
| (2, 0)S(0)  | 1.190         | 14.3 (1.4)                    | 9.3 (1.9)                     |
| (4, 2)S(9)* | 1.196         | 5.6 (1.0)                     | 0.6 (0.1)                     |
| (4, 2)S(10)* | 1.196       | 5.6 (1.0)                     | 0.7 (0.2)                     |
| (4, 2)S(8)* | 1.199         | 3.7 (1.0)                     | 0.3 (0.1)                     |
| (4, 2)S(11)* | 1.199       | 3.7 (1.0)                     | 0.5 (0.1)                     |
| (4, 2)S(7)  | 1.205         | 15.6 (1.6)                    | 1.2 (0.2)                     |
| (3, 1)S(2)  | 1.208         | 13.4 (1.3)                    | 2.0 (0.4)                     |
| (4, 2)S(6)  | 1.214         | 8.0 (1.0)                     | 0.6 (0.1)                     |
| (4, 2)S(5)  | 1.226         | 19.5 (1.9)                    | 1.5 (0.3)                     |
| (3, 1)S(1)  | 1.233         | 30.8 (3.1)                    | 5.7 (1.1)                     |
| (2, 0)Q(1)  | 1.238         | 39.7 (4.0)                    | 17.8 (3.6)                    |
| (2, 0)Q(2)* | 1.242         | 21.2 (2.1)                    | 13.4 (2.7)                    |
| (4, 2)S(4)* | 1.242         | 21.2 (2.1)                    | 1.7 (0.3)                     |
| (2, 0)Q(3)  | 1.247         | 41.8 (4.2)                    | 28.3 (5.7)                    |
| (2, 0)Q(4)  | 1.255         | 14.4 (1.4)                    | 10.1 (2.0)                    |
| (4, 2)S(3)  | 1.262         | 19.9 (2.0)                    | 1.7 (0.3)                     |
| (2, 0)Q(5)  | 1.264         | 38.6 (3.9)                    | 27.8 (5.6)                    |
| (2, 0)Q(6)  | 1.274         | 9.6 (1.0)                     | 7.1 (1.4)                     |
| (5, 3)S(9)  | 1.282         | 3.9 (1.0)                     | 0.4 (0.1)                     |
| (4, 2)S(2)* | 1.285         | 7.7 (1.0)                     | 0.8 (0.2)                     |
| (5, 3)S(10)* | 1.284       | 7.7 (1.0)                     | 0.9 (0.2)                     |
| (2, 0)Q(7)* | 1.287         | 29.5 (3.0)                    | 22.3 (4.5)                    |
| (5, 3)S(7)* | 1.289         | 29.5 (3.0)                    | 2.2 (0.4)                     |
| (2, 0)O(2)  | 1.293         | 7.3 (1.0)                     | 1.9 (0.4)                     |
| (5, 3)S(6)  | 1.298         | 2.9 (1.0)                     | 0.2 (0.0)                     |
| (2, 0)Q(8)  | 1.302         | 6.5 (1.0)                     | 5.1 (1.0)                     |
| (4, 2)S(1)  | 1.312         | 19.8 (2.0)                    | 2.4 (0.5)                     |
| (3, 1)Q(1)  | 1.314         | 15.1 (1.5)                    | 2.8 (0.6)                     |
| (5, 3)S(5)  | 1.311         | 4.0 (1.0)                     | 0.3 (0.1)                     |
| (3, 1)Q(2)* | 1.318         | 15.9 (1.6)                    | 4.1 (0.8)                     |
| (2, 0)Q(9)* | 1.319         | 15.9 (1.6)                    | 12.6 (2.5)                    |
| (3, 1)Q(3)  | 1.324         | 15.1 (1.5)                    | 4.2 (0.8)                     |
| (5, 3)S(4)  | 1.327         | 2.9 (1.0)                     | 0.2 (0.0)                     |
| (3, 1)Q(4)  | 1.332         | 6.0 (1.0)                     | 1.7 (0.3)                     |
| (2, 0)O(3)  | 1.335         | 32.2 (3.2)                    | 18.7 (3.7)                    |
| (2, 0)Q(10) | 1.338         | 4.2 (1.0)                     | 3.5 (0.7)                     |
| (3, 1)Q(5)  | 1.342         | 24.3 (2.4)                    | 7.3 (1.5)                     |
| (5, 3)S(3)  | 1.347         | 8.1 (1.0)                     | 0.6 (0.1)                     |
| (2, 0)Q(12)* | 1.381         | 7.6 (1.0)                     | 6.7 (1.3)                     |
| (2, 0)O(4)* | 1.382         | 7.6 (1.0)                     | 7.1 (1.4)                     |
| (6, 4)S(8)* | 1.384         | 2.2 (1.0)                     | 0.2 (0.1)                     |
| (6, 4)S(9)* | 1.384         | 2.2 (1.0)                     | 0.3 (0.1)                     |
| (6, 4)S(10)* | 1.389       | 2.2 (1.0)                     | 0.4 (0.1)                     |
| (6, 4)S(7)* | 1.388         | 2.2 (1.0)                     | 0.2 (0.0)                     |
| (3, 1)Q(9)  | 1.403         | 9.7 (1.0)                     | 3.3 (0.7)                     |
| (6, 4)S(5)  | 1.408         | 4.1 (1.0)                     | 0.3 (0.1)                     |
| (3, 1)O(3)* | 1.418         | 6.8 (1.0)                     | 1.6 (0.3)                     |
| (4, 2)Q(4)* | 1.418         | 6.8 (1.0)                     | 1.3 (0.3)                     |
Table 1. continued.

| Line                | Wavelength (Å) | Flux $P$ ($10^{-18}$Wm$^{-2}$) | $N(vJ)$ ($10^{14}$cm$^{-2}$) |
|---------------------|----------------|---------------------------------|-------------------------------|
| (3, 1)Q(10)*       | 1.424          | 6.3 (1.0)                       | 2.2 (0.4)                     |
| (6, 4)S(4)*        | 1.425          | 6.3 (1.0)                       | 0.4 (0.1)                     |
| (4, 2)Q(5)         | 1.430          | 7.1 (1.0)                       | 1.4 (0.3)                     |
| (2, 0)O(5)         | 1.432          | 14.0 (1.4)                      | 20.1 (4.0)                    |
| (4, 2)Q(6)         | 1.443          | 3.1 (1.0)                       | 0.6 (0.2)                     |
| (3, 1)Q(11)        | 1.448          | 9.2 (1.0)                       | 3.3 (0.7)                     |
| (4, 2)Q(7)         | 1.459          | 7.3 (1.0)                       | 1.5 (0.3)                     |
| (2, 0)O(6)         | 1.465          | 1.7 (1.0)                       | 1.8 (1.0)                     |
| (3, 1)O(4)         | 1.468          | 2.5 (1.0)                       | 0.9 (0.4)                     |
| (3, 1)Q(12)        | 1.474          | 1.7 (1.0)                       | 0.7 (0.4)                     |
| (2, 0)O(6)         | 1.487          | 3.2 (1.0)                       | 7.1 (2.4)                     |
| (5, 3)Q(1)         | 1.493          | 1.9 (1.0)                       | 0.2 (0.1)                     |
| (4, 2)Q(9)         | 1.499          | 6.1 (1.0)                       | 1.3 (0.3)                     |
| (3, 1)Q(13)        | 1.502          | 6.7 (1.0)                       | 2.7 (0.5)                     |
| (5, 3)Q(3)*        | 1.506          | 3.8 (1.0)                       | 0.5 (0.1)                     |
| (7, 5)S(7)*        | 1.506          | 3.8 (1.0)                       | 0.4 (0.1)                     |
| (4, 2)O(3)         | 1.510          | 5.4 (1.0)                       | 0.7 (0.2)                     |
| (5, 3)Q(4)         | 1.516          | 2.0 (1.0)                       | 0.3 (0.2)                     |
| (3, 1)O(5)         | 1.522          | 13.4 (1.3)                      | 7.2 (1.4)                     |
| (3, 1)Q(14)        | 1.533          | 4.0 (1.0)                       | 1.7 (0.2)                     |
| (5, 3)Q(5)         | 1.529          | 4.9 (1.0)                       | 0.7 (0.1)                     |
| (2, 0)O(7)         | 1.546          | 8.6 (1.0)                       | 29.6 (5.9)                    |
| (4, 2)Q(11)        | 1.549          | 3.6 (1.0)                       | 0.9 (0.2)                     |
| (7, 5)S(3)         | 1.562          | 4.5 (1.0)                       | 0.4 (0.1)                     |
| (4, 2)O(4)         | 1.564          | 2.9 (1.0)                       | 0.6 (0.1)                     |
| (3, 1)Q(15)        | 1.569          | 2.0 (1.0)                       | 0.9 (0.2)                     |
| (5, 3)Q(8)         | 1.584          | 2.3 (1.0)                       | 0.4 (0.1)                     |
| (6, 4)Q(1)         | 1.602          | $\leq$ 1.0                     | $\leq$ 0.1                    |
| (5, 3)Q(9)         | 1.608          | 3.2 (1.0)                       | 0.6 (0.2)                     |
| (2, 0)O(8)*        | 1.610          | 4.0 (1.0)                       | 22.1 (5.0)                    |
| (4, 2)Q(13)*       | 1.612          | 4.0 (1.0)                       | 1.1 (0.2)                     |
| (6, 4)Q(3)         | 1.616          | 2.2 (1.0)                       | 0.3 (0.1)                     |
| (4, 2)O(5)         | 1.622          | 4.7 (1.0)                       | 1.4 (0.3)                     |
| grism HR order 2   |                |                                 |                               |
| (3, 1)O(5)         | 1.522          | 8.4 (0.8)                       | 4.5 (0.9)                     |
| (2, 0)O(7)         | 1.546          | 4.7 (0.5)                       | 16.3 (3.3)                    |
| (4, 2)Q(11)        | 1.549          | 2.4 (0.5)                       | 0.6 (0.1)                     |
| (5, 3)O(2)*        | 1.561          | 1.8 (0.5)                       | 0.1 (0.0)                     |
| (7, 5)S(3)*        | 1.562          | 1.8 (0.5)                       | 0.1 (0.0)                     |
| (5, 3)Q(7)         | 1.563          | 2.5 (0.5)                       | 0.4 (0.1)                     |
| (5, 3)Q(9)         | 1.608          | 1.5 (0.5)                       | 0.3 (0.1)                     |
| (4, 2)Q(13)        | 1.612          | 1.6 (0.5)                       | 0.4 (0.1)                     |
| (6, 4)Q(3)*        | 1.616          | 1.0 (0.5)                       | 0.1 (0.0)                     |
| (2, 0)Q(19)*       | 1.616          | 1.0 (0.5)                       | 1.4 (0.3)                     |
| (7, 5)S(1)         | 1.620          | 1.0 (0.5)                       | 0.1 (0.0)                     |
| (6, 4)Q(5)         | 1.643          | 1.3 (0.5)                       | 0.2 (0.0)                     |
| (3, 1)O(7)         | 1.645          | 3.8 (0.5)                       | 4.6 (0.9)                     |
| (3, 1)Q(17)        | 1.648          | 1.4 (0.5)                       | 0.7 (0.2)                     |
| (4, 2)Q(14)        | 1.649          | 1.7 (0.5)                       | 0.5 (0.1)                     |
| (1, 0)S(11)        | 1.650          | 4.3 (0.5)                       | 9.2 (1.8)                     |
| (1, 0)S(18)        | 1.659          | $\leq$ 0.5                     | $\leq$ 0.2                    |
| (6, 4)Q(6)         | 1.661          | $\leq$ 0.5                     | $\leq$ 0.1                    |
| (1, 0)S(10)        | 1.666          | 6.4 (0.6)                       | 7.1 (1.4)                     |
| (1, 0)S(19)        | 1.675          | 1.5 (0.5)                       | 0.4 (0.1)                     |
| (6, 4)Q(7)         | 1.683          | 2.5 (0.5)                       | 0.4 (0.1)                     |
| (1, 0)S(9)         | 1.688          | 44.9 (4.5)                      | 31.6 (6.3)                    |
| (1, 0)S(8)         | 1.715          | 28.2 (2.8)                      | 14.4 (2.9)                    |
| (2, 1)S(9)         | 1.790          | 12.5 (1.3)                      | 10.4 (2.1)                    |
| (6, 4)O(3)         | 1.733          | 1.2 (0.5)                       | 0.1 (0.0)                     |
Table 1. continued.

| Line          | Wavelength (Å) | Flux $F$ (10^{-19}Wm^{-2}) | $N(\nu J^*)$ (10^{14}cm^{-2}) |
|--------------|----------------|----------------------------|---------------------------------|
| (5, 3)O(5)   | 1.736          | 2.0 (0.5)                  | 0.4 (0.1)                       |
| (6, 4)Q(9)   | 1.737          | 2.0 (0.5)                  | 0.3 (0.1)                       |
| (2, 1)S(15)  | 1.739          | 5.1 (0.5)                  | 3.4 (0.7)                       |
| (5, 3)Q(13)  | 1.741          | 2.0 (0.5)                  | 0.4 (0.1)                       |
| (1, 0)S(7)   | 1.748          | 162.4 (16.2)               | 66.6 (13.3)                     |
| (2, 1)S(11)  | 1.753          | 2.0 (0.5)                  | 11.9 (2.4)                      |
| (4, 2)O(7)   | 1.756          | 4.0 (0.5)                  | 2.6 (0.5)                       |
| (2, 1)S(17)  | 1.759          | 4.0 (0.5)                  | 0.9 (0.2)                       |
| (1, 0)S(6)   | 1.788          | 95.9 (9.6)                 | 33.9 (6.8)                      |
| (2, 1)S(9)   | 1.790          | 10.0 (1.0)                 | 8.3 (1.7)                       |
| (2, 1)S(4)   | 2.004          | 19.4 (1.9)                 | 4.9 (2.4)                       |
| (1, 0)S(2)   | 2.034          | 272.4 (27.2)               | 97.4 (48.7)                     |
| (3, 2)S(5)   | 2.066          | 14.9 (1.5)                 | 4.8 (2.4)                       |
| (2, 1)S(3)   | 2.074          | 103.1 (10.3)               | 25.9 (13.0)                     |
| (1, 0)S(1)   | 2.122          | 647.9 (64.8)               | 277.3 (55.5)                    |
| (3, 2)S(4)   | 2.128          | 4.0 (1.0)                  | 1.1 (0.3)                       |
| (2, 1)S(2)   | 2.154          | 36.4 (3.6)                 | 9.8 (2.0)                       |
| (3, 2)S(3)   | 2.201          | 21.9 (2.2)                 | 6.0 (1.2)                       |
| (1, 0)S(0)   | 2.223          | 130.5 (13.0)               | 80.4 (16.1)                     |
| (2, 1)S(1)   | 2.248          | 90.6 (9.1)                 | 28.7 (5.7)                      |
| (4, 3)S(4)   | 2.267          | 4.0 (1.0)                  | 8.16 (0.3)                      |
| (3, 2)S(2)   | 2.287          | 4.5 (1.0)                  | 1.3 (0.3)                       |

* unresolved line blend
Fig. 8. H$_2$ excitation diagram with values of $lnN(v'J')/g$ plotted versus excitation energy $E(v'J')$. Open triangles represent data points inferred from the column densities $N(v'J')$ listed in Tables 1 and 2. Filled triangles are obtained from a model calculation where the emission arises from a two-component gas model, where the bulk of the material has a total H$_2$ column density of $1.24 \times 10^{18}$ cm$^{-2}$ and is at a temperature of 2750 K, and where a fraction of $10^{16}$ cm$^{-2}$ of H$_2$ is at a temperature of 6000 K.
Online Material
Table 2. Theoretical H$_2$ line fluxes

| Line   | Wavelength (µm) | $E_{upp}$ (cm$^{-1}$) | $F_{2750K}$ (10$^{-19}$Wm$^{-2}$) | $F_{6000K}$ (10$^{-19}$Wm$^{-2}$) | $F_{tot}$ (10$^{-19}$Wm$^{-2}$) |
|--------|-----------------|------------------------|-----------------------------------|-----------------------------------|----------------------------------|
| (0,0)S(2) | 12.279 | 1168.8 | 2.5 | 0.0 | 2.5 |
| (0,0)S(3) | 9.665 | 1740.2 | 30.8 | 0.5 | 31.3 |
| (0,0)S(4) | 8.026 | 2414.8 | 27.6 | 0.5 | 28.1 |
| (0,0)S(5) | 6.909 | 3187.6 | 164.8 | 4.1 | 168.8 |
| (0,0)S(6) | 6.109 | 4051.7 | 87.0 | 2.7 | 89.7 |
| (0,0)S(7) | 5.511 | 5002.0 | 344.7 | 14.2 | 358.9 |
| (0,0)S(8) | 5.053 | 6030.8 | 130.7 | 7.2 | 137.9 |
| (0,0)S(9) | 4.695 | 7132.0 | 393.4 | 29.7 | 423.1 |
| (0,0)S(10) | 4.410 | 8298.6 | 118.3 | 12.4 | 130.7 |
| (0,0)S(11) | 4.181 | 9523.8 | 291.7 | 43.4 | 335.1 |
| (0,0)S(12) | 3.998 | 10800.0 | 73.8 | 15.8 | 89.6 |
| (0,0)S(13) | 3.846 | 12123.7 | 156.8 | 48.7 | 205.5 |
| (0,0)S(14) | 3.736 | 13477.0 | 34.9 | 15.9 | 50.8 |
| (0,0)S(15) | 3.647 | 14866.0 | 66.2 | 44.7 | 111.0 |
| (0,0)S(16) | 3.536 | 16304.8 | 13.3 | 13.5 | 26.9 |
| (0,0)S(17) | 3.467 | 17750.2 | 23.2 | 35.5 | 58.8 |
| (0,0)S(18) | 3.438 | 19213.2 | 4.3 | 10.0 | 14.3 |
| (0,0)S(19) | 3.404 | 20688.0 | 7.0 | 24.7 | 31.7 |
| (1,0)O(2) | 2.627 | 4161.1 | 84.0 | 2.7 | 86.8 |
| (1,0)Q(1) | 2.407 | 4273.8 | 391.1 | 13.1 | 404.2 |
| (1,0)O(3) | 2.803 | 4273.8 | 330.7 | 11.1 | 341.8 |
| (1,0)S(0) | 2.223 | 4497.8 | 123.2 | 4.4 | 127.6 |
| (1,0)Q(2) | 2.413 | 4497.8 | 136.1 | 4.9 | 141.0 |
| (1,0)O(4) | 3.004 | 4497.8 | 104.6 | 3.7 | 108.3 |
| (1,0)S(1) | 2.122 | 4831.4 | 625.5 | 24.6 | 650.1 |
| (1,0)Q(3) | 2.424 | 4831.4 | 439.0 | 17.3 | 456.3 |
| (1,0)O(5) | 3.235 | 4831.4 | 246.3 | 9.7 | 255.9 |
| (1,0)S(2) | 2.034 | 5271.4 | 254.9 | 11.4 | 266.3 |
| (1,0)Q(4) | 2.437 | 5271.4 | 141.6 | 6.3 | 147.9 |
| (1,0)O(6) | 3.501 | 5271.4 | 55.7 | 2.5 | 58.2 |
| (1,0)S(3) | 1.958 | 5813.9 | 772.5 | 40.1 | 812.6 |
| (1,0)Q(5) | 2.455 | 5813.9 | 372.7 | 19.4 | 392.1 |
| (1,0)O(7) | 3.808 | 5813.9 | 100.2 | 5.2 | 105.5 |
| (1,0)S(4) | 1.892 | 6454.3 | 224.3 | 14.0 | 238.2 |
| (1,0)Q(6) | 2.476 | 6454.3 | 100.0 | 6.2 | 106.2 |
| (1,0)O(8) | 4.162 | 6454.3 | 17.9 | 1.1 | 19.0 |
| (1,0)S(5) | 1.836 | 7187.4 | 514.7 | 39.5 | 554.1 |
| (1,0)Q(7) | 2.500 | 7187.4 | 223.6 | 17.1 | 240.7 |
| (1,0)O(9) | 4.576 | 7187.4 | 26.0 | 2.0 | 27.9 |
| (1,0)S(6) | 1.788 | 8007.8 | 116.3 | 11.2 | 127.5 |
| (1,0)Q(8) | 2.528 | 8007.8 | 51.8 | 5.0 | 56.8 |
| (1,0)O(10) | 5.058 | 8007.8 | 3.8 | 0.4 | 4.2 |
| (1,0)S(7) | 1.748 | 8908.3 | 209.8 | 26.2 | 236.0 |
| (1,0)Q(9) | 2.560 | 8908.3 | 101.5 | 12.7 | 114.2 |
| (1,0)O(11) | 5.630 | 8908.3 | 4.5 | 0.6 | 5.1 |
| (1,0)S(8) | 1.715 | 9883.8 | 37.1 | 6.1 | 43.3 |
| (1,0)Q(10) | 2.595 | 9883.8 | 20.9 | 3.4 | 24.3 |
| (1,0)S(9) | 1.688 | 10927.1 | 51.5 | 11.4 | 62.9 |
| (1,0)Q(11) | 2.635 | 10927.1 | 36.7 | 8.1 | 44.8 |
| (1,0)S(10) | 1.666 | 12031.4 | 6.7 | 2.0 | 8.7 |
| (1,0)Q(12) | 2.679 | 12031.4 | 6.8 | 2.1 | 8.9 |
| (1,0)S(11) | 1.650 | 13191.1 | 6.0 | 2.5 | 8.5 |
| (1,0)Q(13) | 2.727 | 13191.1 | 10.9 | 4.6 | 15.5 |
| (1,0)Q(14) | 2.778 | 14399.1 | 1.9 | 1.1 | 3.0 |
| (1,0)Q(15) | 2.836 | 15649.6 | 2.8 | 2.4 | 5.1 |
| (1,0)S(15) | 1.631 | 18253.5 | 0.4 | 0.8 | 1.2 |
| (1,0)Q(17) | 2.952 | 18253.5 | 0.6 | 1.1 | 1.7 |
| (1,0)S(17) | 1.642 | 20957.7 | 0.5 | 2.0 | 2.6 |
| (1,0)S(19) | 1.675 | 23720.3 | 0.3 | 2.6 | 2.9 |
| Line       | Wavelength (µm) | $E_{\text{up}}$ (cm$^{-1}$) | $F_{2750K}$ (10$^{-19}$Wm$^{-2}$) | $F_{6000K}$ (10$^{-19}$Wm$^{-2}$) | $F_{\text{tot}}$ (10$^{-19}$Wm$^{-2}$) |
|------------|-----------------|----------------------------|----------------------------------|----------------------------------|----------------------------------|
| (1,1)S(3) | 10.178          | 5813.9                     | 3.3                              | 0.2                              | 3.4                              |
| (1,1)S(4) | 8.454           | 6454.3                     | 2.9                              | 0.2                              | 3.1                              |
| (1,1)S(5) | 7.281           | 7187.4                     | 17.8                             | 1.4                              | 19.2                             |
| (1,1)S(6) | 6.437           | 8007.8                     | 9.6                              | 0.9                              | 10.5                             |
| (1,1)S(7) | 5.811           | 8908.3                     | 38.5                             | 4.8                              | 43.3                             |
| (1,1)S(8) | 5.330           | 9883.8                     | 14.9                             | 2.4                              | 17.3                             |
| (1,1)S(9) | 4.953           | 10927.1                    | 45.7                             | 10.1                             | 55.8                             |
| (1,1)S(10)| 4.656           | 12031.4                    | 14.0                             | 4.2                              | 18.3                             |
| (1,1)S(11)| 4.417           | 13191.1                    | 35.4                             | 14.9                             | 50.3                             |
| (1,1)S(12)| 4.224           | 14399.1                    | 9.2                              | 5.4                              | 14.6                             |
| (1,1)S(13)| 4.067           | 15649.6                    | 20.0                             | 16.9                             | 36.9                             |
| (1,1)S(14)| 3.941           | 16936.2                    | 4.6                              | 5.5                              | 10.1                             |
| (1,1)S(15)| 3.840           | 18253.5                    | 8.9                              | 15.7                             | 24.6                             |
| (1,1)S(16)| 3.760           | 19595.7                    | 1.8                              | 4.7                              | 6.6                              |
| (1,1)S(17)| 3.698           | 20957.7                    | 3.3                              | 12.5                             | 15.8                             |
| (1,1)S(18)| 3.652           | 22333.8                    | 0.6                              | 3.5                              | 4.2                              |
| (1,1)S(19)| 3.620           | 23720.3                    | 1.1                              | 8.8                              | 9.9                              |
| (1,1)S(20)| 3.600           | 25111.6                    | 0.2                              | 2.4                              | 2.6                              |
| (2,0)O(2) | 1.293           | 8086.9                     | 8.9                              | 0.9                              | 9.8                              |
| (2,0)O(3) | 1.238           | 8193.8                     | 44.2                             | 4.5                              | 48.7                             |
| (2,0)O(4) | 1.335           | 8193.8                     | 33.9                             | 3.5                              | 37.4                             |
| (2,0)O(0)|  1.190           | 8406.3                     | 15.0                             | 1.6                              | 16.7                             |
| (2,0)Q(2) | 1.242           | 8406.3                     | 15.6                             | 1.7                              | 17.3                             |
| (2,0)O(5) | 1.432           | 8722.7                     | 24.3                             | 2.9                              | 27.2                             |
| (2,0)O(2)|  1.138           | 9139.9                     | 36.0                             | 4.8                              | 40.8                             |
| (2,0)Q(4) | 1.255           | 9139.9                     | 17.1                             | 2.3                              | 19.4                             |
| (2,0)O(6)|  1.487           | 9139.9                     | 5.4                              | 0.7                              | 6.2                              |
| (2,0)S(3)|  1.117           | 9654.1                     | 119.4                            | 18.4                             | 137.9                            |
| (2,0)Q(5)|  1.264           | 9654.1                     | 46.8                             | 7.2                              | 54.0                             |
| (2,0)O(7)|  1.546           | 9654.1                     | 9.8                              | 1.5                              | 11.3                             |
| (2,0)S(4)|  1.100           | 10261.2                    | 38.6                             | 7.1                              | 45.7                             |
| (2,0)Q(6)|  1.274           | 10261.2                    | 13.1                             | 2.4                              | 15.5                             |
| (2,0)O(8)|  1.610           | 10261.2                    | 1.8                              | 0.3                              | 2.1                              |
| (2,0)S(5)|  1.085           | 10955.7                    | 100.5                            | 22.4                             | 122.9                            |
| (2,0)Q(7)|  1.287           | 10955.7                    | 30.8                             | 6.9                              | 37.7                             |
| (2,0)O(9)|  1.680           | 10955.7                    | 2.6                              | 0.6                              | 3.1                              |
| (2,0)S(6)|  1.073           | 11731.2                    | 26.4                             | 7.3                              | 33.7                             |
| (2,0)Q(8)|  1.302           | 11731.2                    | 7.6                              | 2.1                              | 9.7                              |
| (2,0)S(7)|  1.064           | 12584.8                    | 57.2                             | 20.2                             | 77.4                             |
| (2,0)Q(9)|  1.319           | 12584.8                    | 15.8                             | 5.6                              | 21.4                             |
| (2,0)S(8)|  1.058           | 13507.4                    | 12.7                             | 5.8                              | 18.5                             |
| (2,0)Q(10)| 1.338            | 13507.4                    | 3.5                              | 1.6                              | 5.1                              |
| (2,0)S(9)|  1.054           | 14493.6                    | 23.5                             | 14.3                             | 37.8                             |
| (2,0)Q(11)| 1.358            | 14493.6                    | 6.6                              | 4.0                              | 10.6                             |
| (2,0)S(10)| 1.052            | 15537.1                    | 4.5                              | 3.7                              | 8.2                              |
| (2,0)Q(12)| 1.381            | 15537.1                    | 1.3                              | 1.1                              | 2.4                              |
| (2,0)S(11)| 1.053            | 16632.1                    | 7.3                              | 8.1                              | 15.4                             |
| (2,0)Q(13)| 1.407            | 16632.1                    | 2.3                              | 2.6                              | 4.9                              |
| (2,0)S(12)| 1.056            | 17771.7                    | 1.2                              | 1.9                              | 3.1                              |
| (2,0)Q(14)| 1.434            | 17771.7                    | 0.4                              | 0.7                              | 1.1                              |
| (2,0)S(13)| 1.061            | 18950.3                    | 1.7                              | 3.7                              | 5.4                              |
| (2,0)Q(15)| 1.465            | 18950.3                    | 0.7                              | 1.5                              | 2.3                              |
| (2,0)S(14)| 1.068            | 20161.8                    | 0.2                              | 0.8                              | 1.0                              |
| (2,0)S(15)| 1.078            | 21400.9                    | 0.3                              | 1.3                              | 1.6                              |
| (2,0)Q(17)| 1.530            | 21400.9                    | 0.2                              | 0.9                              | 1.1                              |
| (2,1)O(2)|  2.786           | 8086.9                     | 15.3                             | 1.5                              | 16.8                             |
| (2,1)Q(1)|  2.551           | 8193.8                     | 70.4                             | 7.2                              | 77.6                             |
Table 2. continued.

| Line  | Wavelength (µm) | $E_{\text{up}}$ (cm$^{-1}$) | $P_{2750K}$ ($10^{-19}$Wm$^{-2}$) | $P_{6000K}$ ($10^{-19}$Wm$^{-2}$) | $P_{\text{tot}}$ ($10^{-19}$Wm$^{-2}$) |
|-------|-----------------|-----------------------------|----------------------------------|----------------------------------|--------------------------------------|
| (2,1)O(3) | 2.974 | 8193.8 | 60.6 | 6.2 | 66.8 |
| (2,1)S(0) | 2.356 | 8406.3 | 21.9 | 2.4 | 24.3 |
| (2,1)Q(2) | 2.559 | 8406.3 | 24.6 | 2.7 | 27.3 |
| (2,1)O(4) | 3.190 | 8722.7 | 19.4 | 2.1 | 21.4 |
| (2,1)Q(3) | 2.570 | 8722.7 | 80.0 | 9.5 | 89.4 |
| (2,1)S(1) | 3.438 | 8722.7 | 46.0 | 5.5 | 51.5 |
| (2,1)S(2) | 2.154 | 9139.9 | 44.7 | 6.0 | 50.6 |
| (2,1)Q(4) | 2.585 | 9139.9 | 26.0 | 3.5 | 29.5 |
| (2,1)O(6) | 3.724 | 9654.1 | 10.5 | 1.4 | 11.9 |
| (2,1)S(3) | 2.074 | 9654.1 | 134.1 | 20.7 | 154.8 |
| (2,1)Q(5) | 2.604 | 9654.1 | 69.2 | 10.7 | 79.9 |
| (2,1)O(7) | 4.054 | 9654.1 | 19.2 | 3.0 | 22.1 |
| (2,1)S(4) | 1.945 | 10955.7 | 86.6 | 19.3 | 105.9 |
| (2,1)Q(7) | 2.654 | 10955.7 | 42.7 | 9.5 | 52.2 |
| (2,1)O(8) | 4.884 | 10955.7 | 5.1 | 1.1 | 6.2 |
| (2,1)S(5) | 1.895 | 11732.1 | 19.0 | 5.3 | 24.3 |
| (2,1)Q(8) | 2.685 | 11732.1 | 10.1 | 2.8 | 12.9 |
| (2,1)O(9) | 1.853 | 12584.8 | 33.0 | 11.7 | 44.7 |
| (2,1)S(6) | 2.720 | 12584.8 | 20.1 | 7.1 | 27.2 |
| (2,1)O(11) | 6.033 | 12584.8 | 0.9 | 0.3 | 1.2 |
| (2,1)S(8) | 1.818 | 13507.4 | 5.5 | 2.5 | 8.0 |
| (2,1)Q(10) | 2.760 | 13507.4 | 4.2 | 1.9 | 6.1 |
| (2,1)S(9) | 1.790 | 14493.6 | 6.8 | 4.1 | 10.9 |
| (2,1)Q(11) | 2.804 | 14493.6 | 7.5 | 4.6 | 12.1 |
| (2,1)O(12) | 1.769 | 15537.1 | 0.7 | 0.3 | 1.3 |
| (2,1)Q(12) | 2.852 | 15537.1 | 1.4 | 1.2 | 2.6 |
| (2,1)Q(13) | 2.906 | 16632.1 | 2.3 | 2.6 | 5.0 |
| (2,1)Q(14) | 2.965 | 17771.7 | 0.4 | 0.6 | 1.0 |
| (2,1)Q(15) | 3.030 | 18950.3 | 0.6 | 1.3 | 2.0 |
| (2,1)S(15) | 1.739 | 21400.9 | 0.3 | 1.5 | 1.8 |
| (2,1)S(17) | 1.759 | 23939.6 | 0.3 | 2.5 | 2.8 |
| (2,1)S(19) | 1.796 | 26524.8 | 0.2 | 2.8 | 3.0 |
| (2,2)S(5) | 7.683 | 10955.7 | 2.1 | 0.5 | 2.6 |
| (2,2)S(6) | 6.798 | 11732.1 | 1.1 | 0.3 | 1.5 |
| (2,2)S(7) | 6.138 | 12584.8 | 4.7 | 1.7 | 6.4 |
| (2,2)S(8) | 5.633 | 13507.4 | 1.9 | 0.9 | 2.7 |
| (2,2)S(9) | 5.239 | 14493.6 | 5.8 | 3.5 | 9.3 |
| (2,2)S(10) | 4.927 | 15537.1 | 1.8 | 1.5 | 3.3 |
| (2,2)S(11) | 4.676 | 16632.1 | 4.7 | 5.2 | 9.9 |
| (2,2)S(12) | 4.475 | 17771.7 | 1.2 | 1.9 | 3.2 |
| (2,2)S(13) | 4.314 | 18950.3 | 2.8 | 6.0 | 8.7 |
| (2,2)S(14) | 4.184 | 20161.8 | 0.6 | 2.0 | 2.6 |
| (2,2)S(15) | 4.081 | 21400.9 | 1.3 | 5.6 | 6.9 |
| (2,2)S(16) | 4.000 | 22661.7 | 0.3 | 1.7 | 2.0 |
| (2,2)S(17) | 3.939 | 23939.6 | 0.5 | 4.5 | 5.0 |
| (2,2)S(18) | 3.896 | 25228.7 | 0.1 | 1.3 | 1.4 |
| (2,2)S(19) | 3.868 | 26524.8 | 0.2 | 3.1 | 3.3 |
| (3,0)Q(1) | 0.850 | 11883.5 | 1.3 | 0.4 | 1.6 |
| (3,0)S(1) | 0.815 | 12384.1 | 3.3 | 1.1 | 4.4 |
| (3,0)Q(3) | 0.856 | 12384.1 | 1.5 | 0.5 | 2.0 |
| (3,0)S(2) | 0.805 | 12778.8 | 1.6 | 0.6 | 2.2 |
| (3,0)S(3) | 0.796 | 13265.3 | 6.0 | 2.6 | 8.5 |
| (3,0)Q(5) | 0.868 | 13265.3 | 1.4 | 0.6 | 2.1 |
| (3,0)S(4) | 0.789 | 13839.2 | 2.1 | 1.1 | 3.2 |
| (3,0)S(5) | 0.784 | 14495.5 | 6.1 | 3.7 | 9.8 |
| (3,0)Q(7) | 0.884 | 14495.5 | 1.0 | 0.6 | 1.6 |
Table 2. continued.

| Line     | Wavelength ($\mu$m) | $E_{\text{up}}$ (cm$^{-1}$) | $F_{2750K}$ ($10^{-18}$Wm$^{-2}$) | $F_{6000K}$ ($10^{-18}$Wm$^{-2}$) | $F_{\text{tot}}$ ($10^{-19}$Wm$^{-2}$) |
|----------|---------------------|-------------------------------|---------------------------------|---------------------------------|----------------------------------|
| (3,0)S(6) | 0.780               | 15228.9                       | 1.3                             | 1.3                             | 3.1                              |
| (3,0)S(7) | 0.778               | 16033.8                       | 3.9                             | 8.1                             | 11.9                             |
| (3,0)Q(9) | 0.906               | 16033.8                       | 0.5                             | 1.1                             | 1.6                              |
| (3,0)S(8) | 0.778               | 18904.0                       | 2.1                             | 5.3                             | 7.4                              |
| (3,0)S(10)| 0.782               | 18816.8                       | 0.9                             | 1.4                             | 2.3                              |
| (3,0)S(11)| 0.786               | 19847.1                       | 2.2                             | 3.0                             | 5.2                              |
| (3,0)S(13)| 0.800               | 22025.0                       | 1.3                             | 1.5                             | 2.8                              |
| (3,1)O(2) | 1.373               | 11782.4                       | 0.9                             | 4.1                             | 5.0                              |
| (3,1)Q(1) | 1.314               | 11883.5                       | 4.5                             | 20.0                            | 24.5                             |
| (3,1)O(3) | 1.418               | 11883.5                       | 3.6                             | 16.2                            | 20.0                             |
| (3,1)S(0) | 1.262               | 12084.7                       | 1.6                             | 6.8                             | 8.4                              |
| (3,1)Q(2) | 1.318               | 12084.7                       | 1.7                             | 7.2                             | 8.9                              |
| (3,1)O(4) | 1.468               | 12084.7                       | 1.2                             | 5.2                             | 6.4                              |
| (3,1)S(1) | 1.233               | 12384.1                       | 9.3                             | 37.2                            | 46.5                             |
| (3,1)Q(3) | 1.324               | 12384.1                       | 6.1                             | 24.5                            | 30.6                             |
| (3,1)O(5) | 1.522               | 12384.1                       | 3.2                             | 12.8                            | 16.0                             |
| (3,1)S(2) | 1.208               | 12778.8                       | 4.6                             | 16.8                            | 21.4                             |
| (3,1)Q(4) | 1.332               | 12778.8                       | 2.3                             | 8.5                             | 10.8                             |
| (3,1)O(6) | 1.581               | 12778.8                       | 0.8                             | 3.1                             | 3.9                              |
| (3,1)S(3) | 1.186               | 13265.3                       | 17.4                            | 57.9                            | 75.3                             |
| (3,1)Q(5) | 1.342               | 13265.3                       | 7.3                             | 24.3                            | 31.6                             |
| (3,1)O(7) | 1.645               | 13265.3                       | 1.8                             | 6.0                             | 7.8                              |
| (3,1)S(4) | 1.167               | 13839.2                       | 1.6                             | 19.7                            | 21.3                             |
| (3,1)Q(6) | 1.354               | 13839.2                       | 4.8                             | 7.3                             | 8.1                              |
| (3,1)O(8) | 1.715               | 13839.2                       | 0.4                             | 1.2                             | 1.6                              |
| (3,1)S(5) | 1.152               | 14495.5                       | 20.8                            | 54.9                            | 65.7                             |
| (3,1)Q(7) | 1.368               | 14495.5                       | 7.0                             | 18.6                            | 25.6                             |
| (3,1)O(9) | 1.790               | 14495.5                       | 0.8                             | 2.0                             | 2.8                              |
| (3,1)S(6) | 1.140               | 15228.9                       | 6.7                             | 15.7                            | 22.4                             |
| (3,1)Q(8) | 1.385               | 15228.9                       | 2.2                             | 5.1                             | 7.3                              |
| (3,1)S(7) | 1.130               | 16033.8                       | 18.4                            | 37.9                            | 56.3                             |
| (3,1)Q(9) | 1.403               | 16033.8                       | 5.8                             | 12.0                            | 17.8                             |
| (3,1)S(8) | 1.124               | 16904.0                       | 5.2                             | 9.6                             | 14.8                             |
| (3,1)Q(10)| 1.422               | 16904.0                       | 1.7                             | 3.1                             | 4.8                              |
| (3,1)S(9) | 1.120               | 17833.8                       | 12.7                            | 20.8                            | 33.5                             |
| (3,1)Q(11)| 1.448               | 17833.8                       | 4.2                             | 6.9                             | 11.1                             |
| (3,1)S(10)| 1.119               | 18816.8                       | 3.2                             | 4.8                             | 8.0                              |
| (3,1)Q(12)| 1.474               | 18816.8                       | 1.2                             | 1.7                             | 2.4                              |
| (3,1)S(11)| 1.121               | 19847.1                       | 6.9                             | 9.4                             | 16.3                             |
| (3,1)Q(13)| 1.502               | 19847.1                       | 2.8                             | 3.8                             | 6.6                              |
| (3,1)S(12)| 1.125               | 20918.2                       | 1.6                             | 2.0                             | 3.6                              |
| (3,1)Q(14)| 1.569               | 22025.0                       | 2.9                             | 3.5                             | 6.4                              |
| (3,1)Q(15)| 1.648               | 24321.2                       | 1.0                             | 1.0                             | 2.0                              |
| (3,2)O(2) | 2.962               | 11782.4                       | 0.6                             | 2.9                             | 3.5                              |
| (3,2)Q(1) | 2.710               | 11883.5                       | 0.6                             | 2.9                             | 3.5                              |
| (3,2)O(3) | 3.164               | 11883.5                       | 2.0                             | 13.4                            | 15.4                             |
| (3,2)S(0) | 2.501               | 12084.7                       | 1.0                             | 4.2                             | 5.2                              |
| (3,2)Q(2) | 2.719               | 12084.7                       | 1.1                             | 4.8                             | 5.9                              |
| (3,2)O(4) | 3.396               | 12084.7                       | 0.9                             | 3.8                             | 4.7                              |
| (3,2)S(1) | 2.386               | 12384.1                       | 5.3                             | 21.2                            | 26.5                             |
| (3,2)Q(3) | 2.731               | 12384.1                       | 4.0                             | 15.9                            | 20.0                             |
| (3,2)O(5) | 3.663               | 12384.1                       | 2.4                             | 9.4                             | 11.8                             |
| (3,2)S(2) | 2.287               | 12778.8                       | 2.4                             | 8.7                             | 11.1                             |
| (3,2)Q(4) | 2.748               | 12778.8                       | 1.5                             | 5.4                             | 6.9                              |
| (3,2)O(6) | 3.972               | 12778.8                       | 0.6                             | 2.2                             | 2.8                              |
| (3,2)S(3) | 2.201               | 13265.3                       | 8.0                             | 26.7                            | 34.7                             |
| (3,2)Q(5) | 2.769               | 13265.3                       | 4.5                             | 15.0                            | 20.0                             |
| (3,2)O(7) | 4.330               | 13265.3                       | 1.3                             | 4.3                             | 5.6                              |
Table 2. continued.

| Line | Wavelength (µm) | $E_{\text{up}}$ (cm$^{-1}$) | $P_{2750K}$ ($10^{-19}$Wm$^{-2}$) | $P_{6000K}$ ($10^{-19}$Wm$^{-2}$) | $P_{\text{tot}}$ ($10^{-19}$Wm$^{-2}$) |
|------|-----------------|--------------------------|-------------------------------|-------------------------------|-------------------------------------|
| (3,2)S(4) | 2.128 | 13839.2 | 5.2 | 2.6 | 7.9 |
| (3,2)Q(6) | 2.795 | 13839.2 | 2.9 | 1.5 | 4.3 |
| (3,2)S(5) | 2.066 | 14495.5 | 11.4 | 7.0 | 18.4 |
| (3,2)Q(7) | 2.825 | 14495.5 | 6.6 | 4.0 | 10.7 |
| (3,2)O(9) | 5.234 | 14495.5 | 0.8 | 0.5 | 1.3 |
| (3,2)S(6) | 2.013 | 15228.9 | 2.4 | 1.8 | 4.2 |
| (3,2)Q(8) | 2.860 | 15228.9 | 1.6 | 1.2 | 2.8 |
| (3,2)S(7) | 1.969 | 16033.8 | 3.8 | 3.6 | 7.5 |
| (3,2)Q(9) | 2.899 | 16033.8 | 3.2 | 3.0 | 6.2 |
| (3,2)S(8) | 1.934 | 16904.0 | 0.6 | 0.7 | 1.2 |
| (3,2)Q(10) | 2.944 | 16904.0 | 0.7 | 0.8 | 1.5 |
| (3,2)S(9) | 1.905 | 17833.8 | 0.5 | 0.8 | 1.4 |
| (3,2)Q(11) | 2.994 | 17833.8 | 1.2 | 2.0 | 3.2 |
| (3,2)Q(13) | 3.110 | 19847.1 | 0.4 | 1.1 | 1.5 |
| (3,2)S(15) | 1.862 | 24321.2 | 0.2 | 1.6 | 1.8 |
| (3,2)S(17) | 1.890 | 26691.8 | 0.1 | 2.2 | 2.3 |
| (3,2)S(19) | 1.940 | 29095.0 | 0.1 | 2.2 | 2.3 |
| (3,3)S(7) | 6.500 | 16033.8 | 0.6 | 0.6 | 1.2 |
| (3,3)S(9) | 5.556 | 17833.8 | 0.8 | 1.2 | 2.0 |
| (3,3)S(11) | 4.967 | 19847.1 | 0.7 | 1.9 | 2.5 |
| (3,3)S(13) | 4.592 | 22025.0 | 0.4 | 2.1 | 2.5 |
| (3,3)S(15) | 4.355 | 24321.2 | 0.2 | 2.0 | 2.2 |
| (3,3)S(17) | 4.218 | 26691.8 | 0.1 | 1.6 | 1.7 |
| (3,3)S(19) | 4.161 | 29095.0 | 0.0 | 1.1 | 1.1 |
| (4,1)Q(1) | 0.903 | 15345.8 | 0.7 | 0.5 | 1.2 |
| (4,1)S(1) | 0.866 | 15818.3 | 1.7 | 1.5 | 3.3 |
| (4,1)Q(3) | 0.910 | 15818.3 | 0.8 | 0.7 | 1.6 |
| (4,1)S(2) | 0.855 | 16190.7 | 0.8 | 0.8 | 1.7 |
| (4,1)S(3) | 0.846 | 16649.5 | 3.1 | 3.5 | 6.5 |
| (4,1)Q(5) | 0.923 | 16649.5 | 0.8 | 0.9 | 1.8 |
| (4,1)S(4) | 0.839 | 17190.4 | 1.1 | 1.4 | 2.5 |
| (4,1)S(5) | 0.834 | 17808.8 | 3.2 | 4.9 | 8.1 |
| (4,1)Q(7) | 0.942 | 17808.8 | 0.6 | 0.9 | 1.5 |
| (4,1)S(6) | 0.830 | 18499.1 | 0.9 | 1.7 | 2.6 |
| (4,1)S(7) | 0.829 | 19256.4 | 2.2 | 5.1 | 7.3 |
| (4,1)Q(9) | 0.966 | 19256.4 | 0.4 | 0.8 | 1.2 |
| (4,1)S(8) | 0.829 | 20074.5 | 0.5 | 1.6 | 2.1 |
| (4,1)S(9) | 0.831 | 20947.5 | 1.1 | 4.2 | 5.4 |
| (4,1)S(10) | 0.834 | 21869.5 | 0.2 | 1.2 | 1.4 |
| (4,1)S(11) | 0.840 | 22834.6 | 0.4 | 2.9 | 3.3 |
| (4,1)S(13) | 0.856 | 24870.3 | 0.1 | 1.6 | 1.8 |
| (4,2)O(2) | 1.461 | 15250.3 | 0.9 | 0.6 | 1.5 |
| (4,2)Q(1) | 1.398 | 15345.8 | 4.0 | 3.1 | 7.1 |
| (4,2)O(3) | 1.510 | 15345.8 | 3.4 | 2.6 | 6.0 |
| (4,2)S(0) | 1.343 | 15535.7 | 1.3 | 1.1 | 2.4 |
| (4,2)Q(2) | 1.403 | 15535.7 | 1.4 | 1.2 | 2.6 |
| (4,2)O(4) | 1.564 | 15535.7 | 1.1 | 0.9 | 2.0 |
| (4,2)S(1) | 1.312 | 15818.3 | 7.0 | 6.2 | 13.2 |
| (4,2)Q(3) | 1.409 | 15818.3 | 4.8 | 4.3 | 9.1 |
| (4,2)O(5) | 1.622 | 15818.3 | 2.8 | 2.4 | 5.2 |
| (4,2)S(2) | 1.285 | 16190.7 | 3.1 | 3.0 | 6.1 |
| (4,2)Q(4) | 1.418 | 16190.7 | 1.6 | 1.6 | 3.2 |
| (4,2)O(6) | 1.686 | 16190.7 | 0.7 | 0.7 | 1.3 |
| (4,2)S(3) | 1.262 | 16649.5 | 10.1 | 11.3 | 21.4 |
| (4,2)Q(5) | 1.430 | 16649.5 | 4.6 | 5.1 | 9.7 |
| (4,2)O(7) | 1.756 | 16649.5 | 1.3 | 1.5 | 2.8 |
| (4,2)S(4) | 1.242 | 17190.4 | 3.3 | 4.3 | 7.5 |
| (4,2)Q(6) | 1.443 | 17190.4 | 1.3 | 1.7 | 3.0 |
| (4,2)S(5) | 1.226 | 17808.8 | 8.5 | 13.2 | 21.7 |
| (4,2)Q(7) | 1.459 | 17808.8 | 3.2 | 5.0 | 8.1 |
| Line | Wavelength (\(\mu m\)) | \(E_{upp}\) (cm\(^{-1}\)) | \(P_{2750K}\) (10\(^{-19}\)Wm\(^{-2}\)) | \(P_{6000K}\) (10\(^{-19}\)Wm\(^{-2}\)) | \(P_{tot}\) (10\(^{-19}\)Wm\(^{-2}\)) |
|------|---------------------|------------------|-----------------|-----------------|-----------------|
| (4,2)O(9) | 1.914 | 17808.8 | 0.4 | 0.7 | 1.1 |
| (4,2)S(6) | 1.214 | 18499.1 | 2.2 | 4.2 | 6.5 |
| (4,2)Q(8) | 1.478 | 18499.1 | 0.8 | 1.5 | 2.3 |
| (4,2)S(7) | 1.205 | 19256.4 | 4.9 | 11.4 | 16.2 |
| (4,2)O(9) | 1.499 | 19256.4 | 1.8 | 4.1 | 5.9 |
| (4,2)S(8) | 1.199 | 20074.5 | 1.1 | 3.2 | 4.3 |
| (4,2)Q(10) | 1.523 | 20074.5 | 0.4 | 1.2 | 1.6 |
| (4,2)S(9) | 1.196 | 20947.5 | 2.0 | 7.6 | 9.6 |
| (4,2)Q(11) | 1.549 | 20947.5 | 0.8 | 3.0 | 3.9 |
| (4,2)S(10) | 1.196 | 21869.5 | 0.4 | 1.9 | 2.3 |
| (4,2)Q(12) | 1.579 | 21869.5 | 0.2 | 0.8 | 1.0 |
| (4,2)S(11) | 1.199 | 22834.6 | 0.6 | 3.9 | 4.5 |
| (4,2)Q(13) | 1.612 | 22834.6 | 0.3 | 2.0 | 2.3 |
| (4,2)S(13) | 1.214 | 24870.3 | 0.1 | 1.5 | 1.6 |
| (4,2)Q(15) | 1.689 | 24870.3 | 0.1 | 1.2 | 1.3 |
| (4,3)Q(1) | 2.888 | 15345.8 | 1.5 | 1.1 | 2.6 |
| (4,3)O(3) | 3.376 | 15345.8 | 1.3 | 1.0 | 2.3 |
| (4,3)S(1) | 2.541 | 15818.3 | 2.2 | 1.9 | 4.1 |
| (4,3)Q(3) | 2.912 | 15818.3 | 1.7 | 1.5 | 3.2 |
| (4,3)O(5) | 3.917 | 15818.3 | 1.0 | 0.9 | 2.0 |
| (4,3)S(2) | 2.435 | 16190.7 | 0.8 | 0.8 | 1.7 |
| (4,3)Q(4) | 2.931 | 16190.7 | 0.6 | 0.6 | 1.1 |
| (4,3)S(3) | 2.344 | 16649.5 | 2.4 | 2.7 | 5.2 |
| (4,3)Q(5) | 2.955 | 16649.5 | 1.5 | 1.7 | 3.2 |
| (4,3)S(4) | 2.267 | 17190.4 | 0.7 | 0.9 | 1.5 |
| (4,3)S(5) | 2.201 | 17808.8 | 1.4 | 2.1 | 3.5 |
| (4,3)Q(7) | 3.018 | 17808.8 | 1.0 | 1.5 | 2.5 |
| (4,3)S(7) | 2.100 | 19256.4 | 0.4 | 0.8 | 1.2 |
| (4,3)Q(9) | 3.103 | 19256.4 | 0.5 | 1.1 | 1.6 |
| (4,3)S(15) | 2.007 | 27008.8 | 0.1 | 1.4 | 1.4 |
| (4,3)S(17) | 2.047 | 29205.3 | 0.0 | 1.6 | 1.6 |
| (4,3)S(19) | 2.116 | 31417.0 | 0.0 | 1.5 | 1.5 |
| (5,1)S(5) | 0.663 | 20894.9 | 0.3 | 1.0 | 1.2 |
| (5,1)S(7) | 0.664 | 22251.2 | 0.2 | 1.2 | 1.4 |
| (5,1)S(9) | 0.670 | 23831.7 | 0.1 | 1.1 | 1.2 |
| (5,2)S(1) | 0.923 | 19026.0 | 0.6 | 1.4 | 2.0 |
| (5,2)Q(3) | 0.971 | 19026.0 | 0.3 | 0.7 | 1.1 |
| (5,2)S(2) | 0.912 | 19376.0 | 0.3 | 0.7 | 1.0 |
| (5,2)S(3) | 0.902 | 19807.0 | 1.1 | 3.1 | 4.2 |
| (5,2)Q(5) | 0.985 | 19807.0 | 0.3 | 0.9 | 1.2 |
| (5,2)S(4) | 0.895 | 20314.8 | 0.4 | 1.3 | 1.7 |
| (5,2)S(5) | 0.890 | 20894.9 | 1.1 | 4.3 | 5.4 |
| (5,2)Q(7) | 1.006 | 20894.9 | 0.2 | 0.9 | 1.2 |
| (5,2)S(6) | 0.886 | 21542.1 | 0.3 | 1.5 | 1.8 |
| (5,2)S(7) | 0.885 | 22251.2 | 0.8 | 4.4 | 5.2 |
| (5,2)S(8) | 0.886 | 23016.2 | 0.2 | 1.4 | 1.6 |
| (5,2)S(9) | 0.889 | 23831.7 | 0.4 | 3.6 | 4.0 |
| (5,2)Q(10) | 0.894 | 24691.8 | 0.1 | 1.0 | 1.1 |
| (5,2)S(11) | 0.901 | 25590.2 | 0.2 | 2.4 | 2.5 |
| (5,2)S(13) | 0.922 | 27479.6 | 0.1 | 1.3 | 1.4 |
| (5,3)Q(1) | 1.493 | 18581.7 | 1.0 | 1.9 | 2.8 |
| (5,3)O(3) | 1.614 | 18581.7 | 0.8 | 1.6 | 2.5 |
| (5,3)Q(2) | 1.498 | 18760.3 | 0.3 | 0.7 | 1.0 |
| (5,3)S(1) | 1.400 | 19026.0 | 1.6 | 3.6 | 5.2 |
| (5,3)Q(3) | 1.506 | 19026.0 | 1.2 | 2.5 | 3.7 |
| (5,3)O(5) | 1.736 | 19026.0 | 0.7 | 1.6 | 2.3 |
| (5,3)S(2) | 1.371 | 19376.0 | 0.7 | 1.7 | 2.4 |
| (5,3)Q(4) | 1.516 | 19376.0 | 0.4 | 1.0 | 1.4 |
| (5,3)S(3) | 1.347 | 19807.0 | 2.3 | 6.3 | 8.6 |
| (5,3)Q(5) | 1.529 | 19807.0 | 1.1 | 3.1 | 4.2 |
Table 2. continued.

| Line    | Wavelength (µm) | \(E_{\text{up}}\) (cm\(^{-1}\)) | \(F_{2750\text{K}}\) \((10^{-19}\text{Wm}^{-2})\) | \(F_{6000\text{K}}\) \((10^{-19}\text{Wm}^{-2})\) | \(F_{\text{tot}}\) \((10^{-19}\text{Wm}^{-2})\) |
|---------|-----------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| (5,3)O (7) | 1.883 | 19807.0 | 0.4 | 1.0 | 1.4 |
| (5,3)S (4) | 1.327 | 20314.8 | 0.7 | 2.3 | 3.1 |
| (5,3)Q (6) | 1.544 | 20314.8 | 0.3 | 1.0 | 1.4 |
| (5,3)S (5) | 1.311 | 20894.9 | 1.9 | 7.1 | 9.0 |
| (5,3)Q (7) | 1.563 | 20894.9 | 0.8 | 3.0 | 3.8 |
| (5,3)S (6) | 1.298 | 21542.1 | 0.5 | 2.2 | 2.7 |
| (5,3)Q (8) | 1.584 | 21542.1 | 0.2 | 0.9 | 1.1 |
| (5,3)S (7) | 1.289 | 22251.2 | 1.1 | 5.9 | 7.0 |
| (5,3)Q (9) | 1.608 | 22251.2 | 0.5 | 2.5 | 3.0 |
| (5,3)S (8) | 1.284 | 23016.2 | 0.2 | 1.6 | 1.9 |
| (5,3)S (9) | 1.282 | 23831.7 | 0.4 | 3.7 | 4.2 |
| (5,3)Q(11) | 1.667 | 23831.7 | 0.2 | 1.9 | 2.1 |
| (5,3)S(11) | 1.289 | 25590.2 | 0.1 | 1.7 | 1.9 |
| (5,3)Q(13) | 1.741 | 25590.2 | 0.1 | 1.2 | 1.3 |
| (5,4)S (3) | 2.507 | 19807.0 | 0.3 | 0.8 | 1.1 |
| (5,4)S(17) | 2.243 | 31466.5 | 0.0 | 1.0 | 1.0 |
| (6,2)S (5) | 0.709 | 23751.0 | 0.1 | 1.1 | 1.2 |
| (6,2)S (7) | 0.711 | 25013.7 | 0.1 | 1.2 | 1.3 |
| (6,2)S (9) | 0.720 | 26480.6 | 0.1 | 1.1 | 1.2 |
| (6,3)S (1) | 0.988 | 22005.6 | 0.2 | 1.1 | 1.3 |
| (6,3)S (3) | 0.966 | 22735.6 | 0.4 | 2.3 | 2.6 |
| (6,3)S (4) | 0.959 | 23209.8 | 0.1 | 0.9 | 1.0 |
| (6,3)S (5) | 0.954 | 23751.0 | 0.4 | 3.1 | 3.4 |
| (6,3)S (6) | 0.951 | 24353.9 | 0.1 | 1.1 | 1.2 |
| (6,3)S (7) | 0.951 | 25013.7 | 0.3 | 3.1 | 3.4 |
| (6,3)S (8) | 0.953 | 25724.3 | 0.1 | 0.9 | 1.0 |
| (6,3)S (9) | 0.957 | 26480.6 | 0.1 | 2.5 | 2.6 |
| (6,3)S(11) | 0.974 | 28105.8 | 0.1 | 1.6 | 1.6 |
| (6,4)Q (1) | 1.602 | 21589.8 | 0.2 | 1.0 | 1.2 |
| (6,4)O (3) | 1.733 | 21589.8 | 0.2 | 0.9 | 1.1 |
| (6,4)S (1) | 1.502 | 22005.6 | 0.4 | 1.9 | 2.2 |
| (6,4)Q (3) | 1.616 | 22005.6 | 0.3 | 1.4 | 1.7 |
| (6,4)O (5) | 1.867 | 22005.6 | 0.2 | 0.9 | 1.1 |
| (6,4)S (2) | 1.471 | 22332.8 | 0.2 | 0.9 | 1.0 |
| (6,4)S (3) | 1.446 | 22735.6 | 0.5 | 3.2 | 3.7 |
| (6,4)Q (5) | 1.643 | 22735.6 | 0.3 | 1.7 | 1.9 |
| (6,4)S (4) | 1.425 | 23209.8 | 0.2 | 1.2 | 1.3 |
| (6,4)S (5) | 1.408 | 23751.0 | 0.4 | 3.5 | 3.9 |
| (6,4)Q (7) | 1.683 | 23751.0 | 0.2 | 1.6 | 1.8 |
| (6,4)S (6) | 1.396 | 24353.9 | 0.1 | 1.1 | 1.2 |
| (6,4)S (7) | 1.388 | 25013.7 | 0.2 | 2.7 | 3.0 |
| (6,4)Q (9) | 1.737 | 25013.7 | 0.1 | 1.4 | 1.5 |
| (6,4)S (9) | 1.384 | 26480.6 | 0.1 | 1.6 | 1.7 |
| (6,4)Q(11) | 1.807 | 26480.6 | 0.1 | 1.0 | 1.1 |
| (7,3)S (7) | 0.767 | 27536.0 | 0.0 | 1.1 | 1.1 |
| (7,3)S (9) | 0.778 | 28884.1 | 0.0 | 1.0 | 1.0 |
| (7,4)S (3) | 1.040 | 25430.1 | 0.1 | 1.5 | 1.6 |
| (7,4)S (5) | 1.029 | 26370.4 | 0.1 | 2.0 | 2.1 |
| (7,4)S (7) | 1.028 | 27536.0 | 0.1 | 1.9 | 2.0 |
| (7,4)S (9) | 1.039 | 28884.1 | 0.0 | 1.5 | 1.6 |
| (7,5)S (3) | 1.562 | 25430.1 | 0.1 | 1.5 | 1.6 |
| (7,5)S (5) | 1.524 | 26370.4 | 0.1 | 1.5 | 1.6 |
| (7,5)S (7) | 1.506 | 27536.0 | 0.0 | 1.1 | 1.2 |
| (8,5)S (5) | 1.119 | 28743.1 | 0.0 | 1.2 | 1.2 |
| (8,5)S (7) | 1.122 | 29806.1 | 0.0 | 1.1 | 1.1 |
Table 3. Theoretical H₂ line fluxes, with modeled fluxes between $(0.5 - 1) \times 10^{-19}$ Wm⁻².

| Line     | Wavelength (µm) | $E_{\text{top}}$ (cm⁻¹) | $F_{2750K}$ (10⁻¹⁹ Wm⁻²) | $F_{6000K}$ (10⁻¹⁹ Wm⁻²) | $F_{\text{tot}}$ (10⁻¹⁹ Wm⁻²) |
|----------|-----------------|--------------------------|--------------------------|--------------------------|-----------------------------|
| (0,0)S(1) | 17.035          | 705.5                    | 0.9                      | 0.0                      | 0.9                         |
| (1,0)O(12)| 6.308           | 9883.8                   | 0.5                      | 0.1                      | 0.6                         |
| (1,0)O(13)| 7.126           | 10927.1                  | 0.5                      | 0.1                      | 0.7                         |
| (1,0)S(12)| 1.639           | 14399.1                  | 0.4                      | 0.2                      | 0.6                         |
| (1,0)Q(16)| 2.891           | 16936.2                  | 0.4                      | 0.5                      | 1.0                         |
| (1,0)S(16)| 1.634           | 19595.7                  | 0.2                      | 0.5                      | 0.7                         |
| (1,0)Q(19)| 3.118           | 20957.7                  | 0.1                      | 0.5                      | 0.6                         |
| (1,0)S(18)| 1.659           | 22333.8                  | 0.1                      | 0.8                      | 1.0                         |
| (1,0)S(20)| 1.695           | 25111.6                  | 0.1                      | 0.9                      | 0.9                         |
| (2,0)O(11)| 1.834           | 12584.8                  | 0.5                      | 0.2                      | 0.6                         |
| (2,0)Q(16)| 1.496           | 20161.8                  | 0.1                      | 0.4                      | 0.5                         |
| (2,0)Q(19)| 1.616           | 23939.6                  | 0.1                      | 0.5                      | 0.5                         |
| (2,1)O(10)| 5.410           | 11732.1                  | 0.8                      | 0.2                      | 1.0                         |
| (2,1)S(11)| 1.753           | 16632.1                  | 0.4                      | 0.4                      | 0.8                         |
| (2,1)Q(17)| 3.177           | 21400.9                  | 0.1                      | 0.6                      | 0.8                         |
| (2,1)S(16)| 1.747           | 22661.7                  | 0.1                      | 0.7                      | 0.8                         |
| (2,1)S(18)| 1.775           | 25228.7                  | 0.1                      | 0.9                      | 1.0                         |
| (2,1)S(20)| 1.822           | 27823.0                  | 0.0                      | 0.9                      | 0.9                         |
| (2,2)S(20)| 3.855           | 27823.0                  | 0.0                      | 0.8                      | 0.9                         |
| (3,0)O(3)| 0.895           | 11883.5                  | 0.5                      | 0.2                      | 0.7                         |
| (3,0)S(0)| 0.827           | 12084.7                  | 0.5                      | 0.2                      | 0.7                         |
| (3,0)Q(2)| 0.852           | 12084.7                  | 0.4                      | 0.1                      | 0.6                         |
| (3,0)Q(4)| 0.861           | 12778.8                  | 0.5                      | 0.2                      | 0.7                         |
| (3,0)Q(6)| 0.875           | 13839.2                  | 0.4                      | 0.2                      | 0.6                         |
| (3,0)Q(11)| 0.934           | 17833.8                  | 0.3                      | 0.4                      | 0.7                         |
| (3,0)S(12)| 0.792           | 20918.2                  | 0.2                      | 0.6                      | 0.7                         |
| (3,0)S(15)| 0.820           | 24321.2                  | 0.1                      | 0.6                      | 0.7                         |
| (3,1)O(11)| 1.958           | 16033.8                  | 0.3                      | 0.3                      | 0.5                         |
| (3,1)Q(14)| 1.534           | 20918.2                  | 0.2                      | 0.7                      | 0.9                         |
| (3,1)S(14)| 1.141           | 23161.0                  | 0.1                      | 0.6                      | 0.7                         |
| (3,1)S(15)| 1.153           | 24321.2                  | 0.1                      | 0.9                      | 1.0                         |
| (3,1)Q(19)| 1.744           | 26691.8                  | 0.0                      | 0.5                      | 0.5                         |
| (3,2)O(8)| 4.746           | 13839.2                  | 0.5                      | 0.3                      | 0.8                         |
| (3,2)Q(12)| 3.049           | 18816.8                  | 0.2                      | 0.5                      | 0.7                         |
| (3,2)S(13)| 1.854           | 22025.0                  | 0.1                      | 0.6                      | 0.8                         |
| (3,2)Q(15)| 3.252           | 22025.0                  | 0.1                      | 0.6                      | 0.7                         |
| (3,2)S(16)| 1.873           | 25499.7                  | 0.0                      | 0.7                      | 0.7                         |
| (3,2)S(18)| 1.912           | 27891.6                  | 0.0                      | 0.8                      | 0.8                         |
| (3,2)S(20)| 1.973           | 30296.3                  | 0.0                      | 0.7                      | 0.7                         |
| (3,3)S(8)| 5.970           | 16904.0                  | 0.3                      | 0.3                      | 0.6                         |
| (3,3)S(10)| 5.228           | 18816.8                  | 0.3                      | 0.5                      | 0.8                         |
| (3,3)S(12)| 4.759           | 20918.2                  | 0.2                      | 0.7                      | 0.9                         |
| (3,3)S(14)| 4.459           | 23161.0                  | 0.1                      | 0.7                      | 0.8                         |
| (3,3)S(16)| 4.276           | 25499.7                  | 0.0                      | 0.6                      | 0.6                         |
| (4,0)S(3)| 0.627           | 16649.5                  | 0.3                      | 0.3                      | 0.6                         |
| (4,0)S(5)| 0.622           | 17808.8                  | 0.4                      | 0.6                      | 0.9                         |
| (4,0)S(7)| 0.622           | 19256.4                  | 0.3                      | 0.7                      | 1.0                         |
| (4,0)S(9)| 0.627           | 20947.5                  | 0.2                      | 0.6                      | 0.8                         |
| (4,0)S(11)| 0.637           | 22834.6                  | 0.1                      | 0.5                      | 0.6                         |
| (4,1)O(3)| 0.951           | 15345.8                  | 0.3                      | 0.3                      | 0.6                         |
| (4,1)S(0)| 0.879           | 15535.7                  | 0.3                      | 0.2                      | 0.5                         |
| (4,1)Q(4)| 0.916           | 16190.7                  | 0.3                      | 0.3                      | 0.6                         |
| (4,1)Q(6)| 0.931           | 17190.4                  | 0.2                      | 0.3                      | 0.6                         |
| (4,1)Q(11)| 0.998           | 20947.5                  | 0.2                      | 0.7                      | 0.8                         |
| (4,1)Q(13)| 1.037           | 22834.6                  | 0.1                      | 0.5                      | 0.5                         |
| (4,1)S(12)| 0.847           | 23836.6                  | 0.1                      | 0.7                      | 0.8                         |
| (4,1)S(15)| 0.880           | 27088.8                  | 0.0                      | 0.8                      | 0.8                         |
| (4,2)O(8)| 1.832           | 17190.4                  | 0.3                      | 0.3                      | 0.6                         |
| (4,2)S(12)| 1.205           | 23836.6                  | 0.1                      | 0.8                      | 0.9                         |
Table 3. continued.

| Line       | Wavelength (\(\mu\)m) | \(E_{\text{up}}\) (cm\(^{-1}\)) | \(F_{2750K}\) (10\(^{-19}\)Wm\(^{-2}\)) | \(F_{6000K}\) (10\(^{-19}\)Wm\(^{-2}\)) | \(F_{\text{tot}}\) (10\(^{-19}\)Wm\(^{-2}\)) |
|------------|------------------------|-----------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| (4,2)Q(14)| 1.649                  | 23836.6                           | 0.1                                      | 0.5                                      | 0.6                                      |
| (4,2)Q(17)| 1.783                  | 27008.8                           | 0.0                                      | 0.7                                      | 0.7                                      |
| (4,3)O(2) | 3.159                  | 15250.3                           | 0.3                                      | 0.2                                      | 0.6                                      |
| (4,3)S(0) | 2.664                  | 15535.7                           | 0.4                                      | 0.4                                      | 0.8                                      |
| (4,3)Q(2) | 2.898                  | 15535.7                           | 0.5                                      | 0.4                                      | 0.9                                      |
| (4,3)O(4) | 3.627                  | 15535.7                           | 0.4                                      | 0.4                                      | 0.8                                      |
| (4,3)O(7) | 4.642                  | 16649.5                           | 0.5                                      | 0.5                                      | 1.0                                      |
| (4,3)Q(6) | 2.984                  | 17190.4                           | 0.4                                      | 0.5                                      | 1.0                                      |
| (4,3)S(6) | 2.146                  | 18499.1                           | 0.3                                      | 0.5                                      | 0.8                                      |
| (4,3)Q(8) | 3.058                  | 18499.1                           | 0.2                                      | 0.4                                      | 0.7                                      |
| (4,3)Q(11)| 3.212                  | 20947.5                           | 0.2                                      | 0.7                                      | 0.9                                      |
| (4,3)S(13)| 1.991                  | 24870.3                           | 0.1                                      | 0.8                                      | 0.8                                      |
| (4,3)S(16)| 2.024                  | 28102.3                           | 0.0                                      | 0.5                                      | 0.5                                      |
| (4,3)S(18)| 2.078                  | 30311.8                           | 0.0                                      | 0.5                                      | 0.5                                      |
| (4,4)S(9) | 5.913                  | 20947.5                           | 0.1                                      | 0.4                                      | 0.6                                      |
| (4,4)S(11)| 5.299                  | 22834.6                           | 0.1                                      | 0.7                                      | 0.8                                      |
| (4,4)S(13)| 4.912                  | 24870.3                           | 0.1                                      | 0.8                                      | 0.8                                      |
| (4,4)S(15)| 4.676                  | 27008.8                           | 0.0                                      | 0.7                                      | 0.7                                      |
| (4,4)S(17)| 4.553                  | 29205.3                           | 0.0                                      | 0.5                                      | 0.6                                      |
| (5,1)S(3) | 0.668                  | 19807.0                           | 0.2                                      | 0.6                                      | 0.8                                      |
| (5,1)S(11)| 0.682                  | 25590.2                           | 0.1                                      | 0.8                                      | 0.9                                      |
| (5,1)S(13)| 0.700                  | 27479.6                           | 0.0                                      | 0.5                                      | 0.6                                      |
| (5,2)Q(1)| 0.963                  | 18581.7                           | 0.3                                      | 0.5                                      | 0.8                                      |
| (5,2)Q(9)| 1.035                  | 22251.2                           | 0.2                                      | 0.8                                      | 1.0                                      |
| (5,2)Q(11)| 1.071                  | 23831.7                           | 0.1                                      | 0.7                                      | 0.7                                      |
| (5,2)Q(13)| 1.116                  | 25590.2                           | 0.0                                      | 0.5                                      | 0.5                                      |
| (5,2)S(12)| 0.910                  | 26521.4                           | 0.0                                      | 0.6                                      | 0.6                                      |
| (5,2)S(15)| 0.952                  | 29453.8                           | 0.0                                      | 0.6                                      | 0.6                                      |
| (5,3)S(0)| 1.433                  | 18760.3                           | 0.3                                      | 0.6                                      | 0.9                                      |
| (5,3)O(4)| 1.672                  | 18760.3                           | 0.3                                      | 0.6                                      | 0.9                                      |
| (5,3)O(6)| 1.806                  | 19376.0                           | 0.2                                      | 0.4                                      | 0.6                                      |
| (5,3)O(9)| 2.057                  | 20894.9                           | 0.1                                      | 0.5                                      | 0.7                                      |
| (5,3)Q(10)| 1.636                  | 23016.2                           | 0.1                                      | 0.7                                      | 0.8                                      |
| (5,3)S(10)| 1.284                  | 24691.8                           | 0.1                                      | 0.9                                      | 1.0                                      |
| (5,3)Q(12)| 1.702                  | 24691.8                           | 0.0                                      | 0.5                                      | 0.6                                      |
| (5,3)S(13)| 1.310                  | 27479.6                           | 0.0                                      | 0.5                                      | 0.5                                      |
| (5,3)Q(15)| 1.833                  | 27479.6                           | 0.0                                      | 0.8                                      | 0.8                                      |
| (5,4)Q(1)| 3.090                  | 18581.7                           | 0.2                                      | 0.4                                      | 0.6                                      |
| (5,4)O(3)| 3.619                  | 18581.7                           | 0.2                                      | 0.4                                      | 0.6                                      |
| (5,4)S(1)| 2.717                  | 19026.0                           | 0.3                                      | 0.6                                      | 0.9                                      |
| (5,4)Q(3)| 3.117                  | 19026.0                           | 0.2                                      | 0.5                                      | 0.8                                      |
| (5,4)Q(5)| 3.167                  | 19807.0                           | 0.2                                      | 0.6                                      | 0.8                                      |
| (5,4)S(5)| 2.355                  | 20894.9                           | 0.1                                      | 0.5                                      | 0.7                                      |
| (5,4)Q(7)| 3.240                  | 20894.9                           | 0.1                                      | 0.5                                      | 0.7                                      |
| (5,4)S(13)| 2.153                  | 27479.6                           | 0.0                                      | 0.7                                      | 0.7                                      |
| (5,4)S(15)| 2.182                  | 29453.8                           | 0.0                                      | 1.0                                      | 1.0                                      |
| (5,4)S(19)| 2.344                  | 33471.2                           | 0.0                                      | 0.9                                      | 0.9                                      |
| (6,2)S(3)| 0.714                  | 22735.6                           | 0.1                                      | 0.7                                      | 0.8                                      |
| (6,2)S(11)| 0.735                  | 28105.8                           | 0.0                                      | 0.9                                      | 0.9                                      |
| (6,2)S(13)| 0.757                  | 29841.8                           | 0.0                                      | 0.6                                      | 0.6                                      |
| (6,3)Q(1)| 1.030                  | 21589.8                           | 0.1                                      | 0.4                                      | 0.5                                      |
| (6,3)Q(3)| 1.039                  | 22005.6                           | 0.1                                      | 0.6                                      | 0.7                                      |
| (6,3)S(2)| 0.976                  | 22332.8                           | 0.1                                      | 0.6                                      | 0.7                                      |
| (6,3)Q(5)| 1.056                  | 22735.6                           | 0.1                                      | 0.7                                      | 0.9                                      |
| (6,3)Q(7)| 1.080                  | 23751.0                           | 0.1                                      | 0.8                                      | 0.9                                      |
| (6,3)Q(9)| 1.114                  | 25013.7                           | 0.1                                      | 0.7                                      | 0.8                                      |
| (6,3)Q(11)| 1.157                  | 26480.6                           | 0.0                                      | 0.6                                      | 0.6                                      |
| (6,3)S(10)| 0.964                  | 27276.4                           | 0.0                                      | 0.7                                      | 0.7                                      |
| (6,3)S(13)| 1.001                  | 29841.8                           | 0.0                                      | 0.8                                      | 0.8                                      |
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Table 3. continued.

| Line      | Wavelength (µm) | \(E_{\text{upp}}\) (cm\(^{-1}\)) | \(F_{2750K}\) (10\(^{-19}\)Wm\(^{-2}\)) | \(F_{6000K}\) (10\(^{-19}\)Wm\(^{-2}\)) | \(F_{\text{tot}}\) (10\(^{-19}\)Wm\(^{-2}\)) |
|-----------|-----------------|-----------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| (6,4)Q(4) | 1.628           | 22332.8                           | 0.1                                  | 0.5                                  | 0.6                                  |
| (6,4)O(7) | 2.030           | 22735.6                           | 0.1                                  | 0.6                                  | 0.7                                  |
| (6,4)Q(6) | 1.661           | 23209.8                           | 0.1                                  | 0.5                                  | 0.6                                  |
| (6,4)Q(8) | 1.708           | 24353.9                           | 0.1                                  | 0.7                                  | 0.8                                  |
| (6,4)S(8) | 1.384           | 25724.3                           | 0.0                                  | 0.6                                  | 0.6                                  |
| (6,4)S(11)| 1.397           | 28105.8                           | 0.0                                  | 0.5                                  | 0.6                                  |
| (6,4)Q(13)| 1.897           | 28105.8                           | 0.0                                  | 0.7                                  | 0.7                                  |
| (6,5)S(13)| 2.352           | 29841.8                           | 0.0                                  | 0.5                                  | 0.5                                  |
| (6,5)S(15)| 2.403           | 31641.1                           | 0.0                                  | 0.6                                  | 0.6                                  |
| (6,5)S(17)| 2.500           | 33453.8                           | 0.0                                  | 0.6                                  | 0.6                                  |
| (7,3)S(3) | 0.767           | 25430.1                           | 0.0                                  | 0.6                                  | 0.6                                  |
| (7,3)S(5) | 0.763           | 26370.4                           | 0.1                                  | 0.9                                  | 1.0                                  |
| (7,3)S(6) | 0.798           | 30368.2                           | 0.0                                  | 0.7                                  | 0.7                                  |
| (7,4)S(1) | 1.063           | 24752.5                           | 0.1                                  | 0.7                                  | 0.8                                  |
| (7,4)Q(5) | 1.139           | 25430.1                           | 0.0                                  | 0.6                                  | 0.6                                  |
| (7,4)S(4) | 1.033           | 25869.5                           | 0.0                                  | 0.6                                  | 0.6                                  |
| (7,4)Q(7) | 1.168           | 26370.4                           | 0.0                                  | 0.6                                  | 0.6                                  |
| (7,4)S(6) | 1.027           | 26927.7                           | 0.0                                  | 0.7                                  | 0.7                                  |
| (7,4)Q(9) | 1.208           | 27536.0                           | 0.0                                  | 0.5                                  | 0.6                                  |
| (7,4)S(8) | 1.032           | 28190.1                           | 0.0                                  | 0.6                                  | 0.6                                  |
| (7,4)S(11)| 1.061           | 30368.2                           | 0.0                                  | 0.9                                  | 0.9                                  |
| (7,5)Q(1) | 1.729           | 24366.1                           | 0.1                                  | 0.5                                  | 0.6                                  |
| (7,5)O(3) | 1.873           | 24366.1                           | 0.1                                  | 0.5                                  | 0.6                                  |
| (7,5)S(1) | 1.621           | 24752.5                           | 0.1                                  | 0.9                                  | 1.0                                  |
| (7,5)Q(3) | 1.746           | 24752.5                           | 0.1                                  | 0.7                                  | 0.8                                  |
| (7,5)O(5) | 2.022           | 24752.5                           | 0.0                                  | 0.5                                  | 0.6                                  |
| (7,5)Q(5) | 1.778           | 25430.1                           | 0.1                                  | 0.9                                  | 0.9                                  |
| (7,5)S(4) | 1.540           | 25869.5                           | 0.0                                  | 0.5                                  | 0.6                                  |
| (7,5)Q(7) | 1.826           | 26370.4                           | 0.0                                  | 0.8                                  | 0.9                                  |
| (7,5)Q(9) | 1.892           | 27536.0                           | 0.0                                  | 0.7                                  | 0.7                                  |
| (7,5)S(9) | 1.508           | 28884.1                           | 0.0                                  | 0.5                                  | 0.6                                  |
| (7,5)Q(11)| 1.979           | 28884.1                           | 0.0                                  | 0.5                                  | 0.5                                  |
| (8,4)S(3) | 0.829           | 27881.7                           | 0.0                                  | 0.5                                  | 0.5                                  |
| (8,4)S(5) | 0.827           | 28743.1                           | 0.0                                  | 0.7                                  | 0.8                                  |
| (8,4)S(7) | 0.834           | 29806.1                           | 0.0                                  | 0.8                                  | 0.8                                  |
| (8,4)S(9) | 0.850           | 31027.0                           | 0.0                                  | 0.7                                  | 0.7                                  |
| (8,4)S(11)| 0.876           | 32358.5                           | 0.0                                  | 0.5                                  | 0.5                                  |
| (8,5)S(3) | 1.129           | 27881.7                           | 0.0                                  | 0.9                                  | 1.0                                  |
| (8,5)S(9) | 1.139           | 31027.0                           | 0.0                                  | 0.8                                  | 0.8                                  |
| (8,6)S(3) | 1.702           | 27881.7                           | 0.0                                  | 0.6                                  | 0.7                                  |
| (8,6)S(5) | 1.665           | 28743.1                           | 0.0                                  | 0.6                                  | 0.6                                  |
| (9,5)S(5) | 0.905           | 30854.1                           | 0.0                                  | 0.5                                  | 0.5                                  |
| (9,5)S(7) | 0.917           | 31805.9                           | 0.0                                  | 0.6                                  | 0.6                                  |
| (9,6)S(3) | 1.239           | 30077.2                           | 0.0                                  | 0.6                                  | 0.6                                  |
| (9,6)S(5) | 1.232           | 30854.1                           | 0.0                                  | 0.7                                  | 0.7                                  |
| (9,6)S(7) | 1.241           | 31805.9                           | 0.0                                  | 0.6                                  | 0.6                                  |
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Fig. 10. Residuals between observed and modeled H$_2$ spectra as shown in Fig. 1, covering the range of 7760–8160 Å. The expected position of the (3,0) S(1)–S(14) lines are indicated.
Fig. 11. Residuals between observed and modeled H$_2$ spectra as shown in Fig. 2, covering the range of 8390–8820 Å. The expected position of various emission lines in the (3,0) and (4,1) bands are indicated. The feature near 8510 Å is a spike and does not correspond to an H$_2$ emission line.
Residuals between observed and modeled H$_2$ spectra as shown in Fig. 3, covering the range of 9400–12800 Å. The modeled flux in the (3,1) S(9), S(10), S(11) blend near 11 200 Å is too high by about a factor of 2.
Fig. 13. Residuals between observed and modeled H$_2$ spectra as shown in Fig. 4, covering the range of 12 800–15 000 Å. The modeled flux in the (3,1) Q(7) line is too high by about a factor of 2. The spectral region between 13 500–14 500 Å is characterised by poor atmospheric transmission.
Fig. 14. Residuals between observed and modeled H$_2$ spectra as shown in Fig. 5, covering the range of 15 000–16 600 Å. The flux in the (3,1) O(5) and (2,0) O(7) lines is too strong by about a factor of 2.
Fig. 15. Residuals between observed and modeled H$_2$ spectra as shown in Fig. 6, covering the range of 16 350–18 000 Å. The line wings in the (1,0) S(7) and S(8) lines show line wings arise from an instrumental defect of SOFI and have no astrophysical significance.
**Fig. 16.** Residuals between observed and modeled H$_2$ spectra as shown in Fig. 7, covering the range of 20 000–23 000 Å. The broad line wings in the (1,0) S(1) line arise from an instrumental defect of SOFI.