Fluorescent \( \text{H}_2 \) in the reflection nebula NGC 2023 – I. Recent observations

M. S. K. McCartney,\(^1\) P. W. J. L. Brand,\(^1\) M. G. Burton\(^2\) and A. Chrysostomou\(^3\)

\(^1\)Institute for Astronomy, Edinburgh University, Blackford Hill, Edinburgh EH9 3HJ
\(^2\)School of Physics, University of New South Wales, Sydney, NSW 2052, Australia
\(^3\)Joint Astronomy Centre, 660 N. A`ohokū Place, University Park, Hilo, HI 96720, USA

Accepted 1999 February 16. Received 1999 February 16; in original form 1998 December 1

ABSTRACT

The spectrum of fluorescent molecular hydrogen in the photodissociation region (PDR) in NGC 2023 is presented. 87 \( \text{H}_2 \) lines have been measured from the bright \( \text{H}_2 \) emission ridge 80 arcsec south of the illuminating star (HD 37903). Infrared images of the PDR taken with 1-0 S(1) and 2.1-\( \mu \)m continuum filters are presented. The infrared and far-red line fluxes provide column densities for 66 rovibrational states of the \( \text{H}_2 \) molecule from vibrational levels within the range \( v = 1-12 \).


1 INTRODUCTION

NGC 2023 is a well-studied, bright reflection nebula at a distance of 450–500 pc (Racine 1968; Lee 1968; de Boer 1983) in the Orion region (see Goudis et al. 1982 for an overview), situated 14 arcmin north-east of the Horsehead nebula. It is embedded on the near-side edge of the dark cloud Lynds 1630, which is a site of recent star formation (Strom et al. 1975) and shows many features including molecular outflows, bright reflection nebulae and Herbig–Haro objects. NGC 2023 is illuminated by HD 37903, a B1.5 V spectral type star (Sharpless 1952) and a highly reddened pre-main-sequence star, S108 (Scarrott, Rolph & Mannion 1989; Sellgren, Werner & Dinerstein 1992). It contains a cluster of 16 young stars (Sellgren, Werner & Dinerstein 1983), and a 10 \( \text{km} \text{s}^{-1} \) outflow has been detected 0.5 arcmin south-west of HD 37903 (Bally & Lada 1983).

NGC 2023 is the site where fluorescent \( \text{H}_2 \) emission was initially detected (Sellgren 1986; Gatley et al. 1987; Gatley & Kaifu 1987; Hasegawa et al. 1987). These infrared detections were followed by the first optical detections of over 30 lines arising from high-excitation levels of \( \text{H}_2 \) (Burton et al. 1992). It is also the site where the ‘extended red emission’ (ERE: 6000–7400 Å) was observed with the cooled grating spectrometer CGS4 (Wright 1994) and with the infrared camera IRCAM3 (Puxley et al. 1994) on the United Kingdom Infrared Telescope (UKIRT) in Hawaii. These observations were made on 1995 October 14 and 15. The same object was observed with the RGO Spectrograph (Stathakis 1997) on the Anglo-Australian Telescope on 1996 January 30 and 31.

2 OBSERVATIONS AND DATA REDUCTION

The bright ridge in NGC 2023, 78 arcsec south and 8 arcsec west of the central star HD 37903 [RA(1950) = 5°39′7″, Dec.(1950) = −2°16′58″], was observed with the cooled grating spectrometer CGS4 (Wright 1994) and with the infrared camera IRCAM3 (Puxley et al. 1994) on the United Kingdom Infrared Telescope (UKIRT) in Hawaii. The ERE observations were made on 1995 October 14 and 15. The same object was observed with the RGO Spectrograph (Stathakis 1997) on the Anglo-Australian Telescope on 1996 January 30 and 31.

2.1 IRCAM3 images

The observations were made at an air mass of 1.1, in 1-arcsec seeing conditions. The entire 256 × 256 pixel array was illuminated at a scale of 0.286 arcsec per pixel. Images were taken with the 1–0 S(1) line filter and the 2.1-\( \mu \)m continuum filter at 2.122 and 2.104 \( \mu \)m respectively with 1 per cent band widths. The exposure times were 50 s to be background-limited. HD 37903 was used as a standard and observed in the line filter once before and once after observing the \( \text{H}_2 \) ridge.

The image frames were reduced using the IRCAM3R package (Aspin 1996). The exposures were dark-subtracted and a flat-field frame was constructed from the resulting frames. ‘Ghost’ images of a star (presumably stray light entering the telescope beam from a bright, nearby star, e.g. Zeta Orionis) were removed from these frames. The two 1–0 S(1) images were then centroided and overlaid.

Since the filter widths were not equal, the intensity of the continuum image was multiplied by 1.14, and then the continuum image was subtracted from the line image. The multiplication factor was determined iteratively to give the minimum stellar
Figure 1. 2.1-μm continuum filter image. The coordinates are relative to HD 37903 (see text for details). The flux range from the darkest to the lightest parts of the extended emission is chosen to be $2.9 \times 10^{-17}$ W m$^{-2}$ μm$^{-1}$ per pixel, to show maximum detail. (The stellar images are saturated on this grey-scale.)

Figure 2. Continuum-subtracted 1–0 S(1) filter image. The grey-scale flux range is 0 to $4.1 \times 10^{-19}$ W m$^{-2}$ per pixel. Residual stellar images have been masked out by discs.
residuals. The continuum and continuum-subtracted images are shown in Figs 2 and 3. Fig. 3 shows a mosaic of the whole region in the 1–0 S(1) line.

The spectrum frames were reduced using the Anglo-Australian Observatory FIGARO package (Shortridge et al. 1997).

2.2 CGS4 spectra

The observations were made with UKIRT at an airmass of 1.3, in 1.5-arcsec seeing conditions. The 75 line mm$^{-1}$ grating was used with the 150-mm focal length camera. This configuration allowed

![Figure 3. 1–0 S(1) filter image of NGC 2023: the emission ridge and HD 37903. The flux range from the darkest to the lightest parts of the extended emission is chosen to be $6 \times 10^{-15} \text{W m}^{-2}$ per pixel, to show maximum detail. (The stellar images are saturated on this grey-scale.)](https://academic.oup.com/mnras/article/307/2/315/1103806)
Figure 4. The $H$-band spectrum of NGC 2023, taken with CGS4. The intensity is in units of flux per $\mu$m per $1.23 \times 1.23$arcsec$^2$ pixel (the line at 1.5833 $\mu$m is a residual strong sky OH line).
Figure 5. The spectrum of NGC 2023, taken with the RGO Spectrograph at the 7323–7961 Å grating position. The intensity is in units of flux per ångström per 0.61 × 1.5 arcsec² pixel.
Figure 6. The spectrum of NGC 2023, taken with the RGO Spectrograph at the 7830–8464 Å grating position. The intensity is in units of flux per ångstrom per $0.61 \times 1.5$ arcsec$^2$ pixel.
Figure 7. The spectrum of NGC 2023, taken with the RGO Spectrograph at the 8404–9033 Å grating position. The intensity is in units of flux per ångstrom per 0.61 × 1.5 arcsec² pixel.
the whole $H$ band to be observed at one grating position with a resolution of $\lambda/\Delta\lambda = 910$, covering the wavelength range 1.44–1.78 $\mu$m. The full 90-arcsec slit was used to illuminate the pixel array with a scale of 1.23 arcsec per pixel and a slit width corresponding to one pixel. The slit was orientated 76° west of north along the $H_2$ emission ridge to include the star S108.

The CGS4 data reduction software automatically applied bad pixel masks to the data, and flat-fielded the data using the blackbody source housed in the calibration unit. The observations were oversampled (the detector was stepped six times over 2 pixels) and the data taken at different detector positions were automatically interleaved. Sky emission was subtracted from observations taken adjacent in time, and line curvature owing to optical distortion was removed from both axes of the data array. A beam of $38.1 \times 1.23$ arcsec$^2$ was used to extract the spectrum of maximum signal-to-noise ratio from the data gathered along the ridge, beginning 4.9 arcsec from the star, S108. The resulting spectrum (Fig. 4) was flux-calibrated using a spectral type A0 star, HD 40335 ($m_H = 6.473$), and flux values of the zero-magnitude star Vega (Mountain et al. 1985). The measured stellar flux was multiplied by a factor of 1.67 to allow for the fact that not all the starlight passes through the slit.

2.3 RGO spectrograph data

On 1996 January 30 and 31 the Anglo-Australian Telescope (AAT) was used with the RGO Spectrograph to observe the ridge of bright fluorescent $H_2$ in NGC 2023. The observations were taken using the 1200 line mm$^{-1}$ (1200R) grating, in first order, with the 25-cm camera at the $f/8$ Cassegrain focus. The Red Thomson 1024×1024 CCD was chosen as a detector. Four grating positions were used over both nights to cover the wavelength range 7300–9600 Å with resolutions of $\lambda/\Delta\lambda = 4000–7000$. A 250-arcsec slit was used to illuminate the CCD with a pixel scale of 0.61 arcsec and a slit width of 1.5 arcsec. The slit contained the star S108 and was orientated 78° west of north to match to observations of Burton et al. (1992). The source was observed for $4 \times 1000$ s at each grating position. The high resolution made oversampling unnecessary, and the long slit permitted the source to be observed simultaneously with the sky background. Before and after each observation of NGC 2023, the standard star HD 40335 was observed. NGC 2023 was observed at four grating positions, giving priority to the wavelength regions with the greatest number of bright $H_2$ lines where the detector had a high quantum efficiency. The last three grating positions (7830–9600 Å) were observed in 2-arcsec seeing conditions, and the first grating position (7320–7960 Å) was observed with 3-arcsec seeing. The resulting spectra for each grating position are shown in Figs 5–8.

The frames were first bias-subtracted. For each grating position a flat-field frame was generated by exposing to a blackbody source. The frame was normalized by dividing by a frame that was the product of the smoothed sum of all the rows along the dispersion direction and the smoothed sum of all the columns along the sky direction. The data frames were flat-fielded by

![Figure 8](https://academic.oup.com/mnras/article/307/2/315/1103806)

**Figure 8.** The spectrum of NGC 2023, taken with the RGO Spectrograph at the 8965–9277 Å grating position. The intensity is in units of flux per ångstrom per 0.61 $\times$ 1.5 arcsec$^2$ pixel.

© 1999 RAS, MNRAS 307, 315–327
division by this frame. Cosmic ray events were removed by interpolation.

Consecutive observations were made with the object projected alternately on two positions along the slit. The source size is smaller than the distance, 90 arcsec, between these positions. A first-order sky subtraction was carried out by subtracting consecutive frames. Optical distortion was corrected for by fitting parabola across sky emission lines and rebinning the data so that the sky lines appeared straight across the data array. This left two images of the source, one reversed, plus sky emission resulting from sky variations between frames. The frame was cut along the dispersion direction, and one part shifted to superpose the negative source on the image of the positive one. The shift was accurately determined using the continuum of the star S108. The parts were then subtracted, co-adding the source and subtracting the residual sky emission. Small remaining sky residuals are due to changes of gradients in sky emission along the slit.

The wavelength scale was calibrated against a copper–argon arc lamp spectrum using a parabola to interpolate between the identified arc lines. All the grating positions were wavelength-calibrated to an rms deviation of less than 0.5 Å.

Of the 250 arcsec of the slit, 57 arcsec contained detectable [C i] 8729 Å emission, in the grating position with the best signal-to-noise ratio (8403–9031 Å). However, the greatest signal-to-noise ratio in the H2 lines was achieved by integrating the emission along 38 arcsec of the slit. This was taken between 5 and 43 arcsec away from S108, the star at the end of the ridge. The source size is 1±0 S(1) line image. The H2 emission ridge, from Figs 1 and 3 display the IRCAM3 images taken in the 2.1–

Parabola were used to fit the wavelengths in each of the J-band grating positions with a scale of 0.62 Å per pixel. 90 lines were identified, of which 60 were considered reliable, with fluxes greater than 3 times the noise level and which did not appear to suffer contamination owing to sky emission or blending with nearby lines. The wavelengths of these lines deviated by no more than 0.7 Å from the calibrated wavelength. The rms deviation for the different grating positions varied between 0.2 and 0.4 Å.

The H-band spectrum was also wavelength-calibrated by fitting a parabola to the wavelength scale. 38 lines were identified, of which 27 were considered reliable at the 3σ detection level and were within 3 Å from the calibrated wavelength. The overall rms deviation of the line centres was 2 Å, for a pixel scale of 4.4 Å.

The H2 lines were observed with spectral resolutions at which they were unresolved, their FWHM being less than 16 km s⁻¹ (Burton et al. 1990). The column densities of H2 in the upper energy levels of the transitions, Nji, are derived from measured specific intensities, Iji, through the equation

\[
n_j = \frac{4\pi I_{ji}}{A_{ji} h v_j \Omega}.
\]

Here \( \Omega \) is the beam solid angle, \( h \) is the Planck constant and \( v_j \) is the frequency of the transition from the jth upper level to the kth lower level of the hydrogen molecule. The transition rate coefficients, \( A_{ji} \), were taken from Abgrall & Roueff (1989) for \( J < 15 \). An electronic version of these data was kindly provided by Roueff (private communication). The transition rate coefficients for \( J \geq 15 \) were taken from Turner, Kirby-Donck & Dalgarno (1977).

The observations described above were taken with exposures sufficiently long to ensure that the dominant noise was from sky background. The errors quoted for the line fluxes are derived from the 1σ error bars in the spectra, found close to the line, multiplied by the square root of the number of pixels used in integrating the flux in the line. It was assumed that systematic errors would put a lower limit on the uncertainty in the column density of any energy level of 10 per cent.

3 RESULTS AND DISCUSSION

3.1 Images

Figs 1 and 3 display the IRCAM3 images taken in the 2.1-μm continuum and 1–0 S(1) line filter. Fig. 2 shows the continuum-subtracted 1–0 S(1) line image. The H2 emission ridge, from which the spectroscopic measurements were taken, shows up brightly in the line filter and to some degree in the continuum filter. This is being irradiated by HD 37903, the star at the centre of NGC 2023. This star is responsible for producing the exciting UV radiation which is causing the fluorescence and illuminating the nebula. The star at the west end of the ridge, S108 (Strom et al. 1975), also known as Selligren’s Star C and HBC 500, is an emission-type star and may contribute to the fluorescence a few arcseconds around it but does not appear to contribute significantly to the emission ridge. Fig. 3 is a mosaic in the 1–0 S(1) filter of the emission ridge and HD 37903. The image of HD 37903 within Fig. 3 was constructed from a set of observations with shorter exposure times, and has a lower signal-to-noise ratio than the image of the H2 emission ridge. Some of the point-like
Table 1. Intensities measured in the brightest 63 pixels, i.e. area 1.5 by (0.61 \times 0.63) arcsec$^2$, by the RGO Spectrometer adjusted for a slit transmission factor of 0.6. The column densities have been calculated assuming an ortho/para ratio of 2.0. Wavelengths are quoted in vacuo. No extinction correction has been applied.

<table>
<thead>
<tr>
<th>Line</th>
<th>$\lambda$ (µm)</th>
<th>Energy (K)</th>
<th>$A_{\nu} \times 10^{-7}$ (s$^{-1}$)</th>
<th>Intensity $\times 10^{-9}$ (W m$^{-2}$sr$^{-1}$)</th>
<th>Error (%)</th>
<th>$\log (N_{j}/g_{j})$ [log (cm$^{-2}$)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7–3 S(5)</td>
<td>0.7631</td>
<td>37941</td>
<td>3.763</td>
<td>0.49</td>
<td>16</td>
<td>11.32</td>
</tr>
<tr>
<td>9–4 S(11)</td>
<td>0.7633</td>
<td>48987</td>
<td>3.782</td>
<td>0.27</td>
<td>40</td>
<td>10.80</td>
</tr>
<tr>
<td>7–3 S(2)</td>
<td>0.7709</td>
<td>36050</td>
<td>2.002</td>
<td>0.28</td>
<td>14</td>
<td>11.88</td>
</tr>
<tr>
<td>3–0 S(7)</td>
<td>0.7784</td>
<td>23069</td>
<td>1.093</td>
<td>0.39</td>
<td>18</td>
<td>11.67</td>
</tr>
<tr>
<td>3–0 S(9)</td>
<td>0.7793</td>
<td>25659</td>
<td>1.161</td>
<td>0.43</td>
<td>27</td>
<td>11.59</td>
</tr>
<tr>
<td>3–0 S(6)</td>
<td>0.7804</td>
<td>21911</td>
<td>1.014</td>
<td>0.28</td>
<td>34</td>
<td>11.91</td>
</tr>
<tr>
<td>3–0 S(5)</td>
<td>0.7840</td>
<td>20856</td>
<td>0.910</td>
<td>0.62</td>
<td>13</td>
<td>12.05</td>
</tr>
<tr>
<td>3–0 S(4)</td>
<td>0.7892</td>
<td>19911</td>
<td>0.786</td>
<td>0.26</td>
<td>31</td>
<td>12.10</td>
</tr>
<tr>
<td>3–0 S(3)</td>
<td>0.7962</td>
<td>19086</td>
<td>0.650</td>
<td>0.68</td>
<td>17</td>
<td>12.38</td>
</tr>
</tbody>
</table>

© 1999 RAS, MNRAS 307, 315–327
sources within it may be ghost reflections. The structure of the \(\text{H}_2\) emission, which is strikingly filamentary, may be due to sheets of \(\text{H}_2\) which have folded, displaying limb-brightened edges. An alternative is that these filaments are higher density regions. Differentiating between these two scenarios is important, and could be done by observing lines from the fainter emission.

### 3.2 Spectra and line fluxes

Figs 5–8 show \(I\)-band spectra taken at four overlapping grating positions, with the RGO Spectrograph. The wavelength axis has been calibrated for light in vacuo by CGS4 adjusted for a slit transmission factor of 0.6. The column densities have been calculated for a slit transmission factor of 0.6. The column densities have been calculated by using equation (1) and dividing the results by the statistical weights of the respective levels, assuming an ortho/para abundance ratio of 2.0 (see below).

### 3.3 Column density plots

Figs 9 and 10 show column densities derived from the \(\text{H}_2\) lines in the far-red and infrared spectra respectively. These have been plotted on a logarithmic axis against the excitation energy of the rovibrational states. The column density has been divided by the statistical weight, which for each level in warm gas \((T \approx 200\,\text{K})\) at thermodynamic equilibrium is the product of the rotational and spin degeneracies, i.e. \(g_r = g_s/(2J + 1)\) where \(J\) is the rotational quantum number and \(g_s\) is the spin degeneracy (i.e. 3 for ortho-\(\text{H}_2\) and 1 for para-\(\text{H}_2\)). However, for gas in a photodissociation region (PDR) the observed ortho/para abundance ratio is not necessarily 3. This is shown by observations of PDRs which provide consistently low values ranging from 1.7 to 2.4 (Hoban et al. 1991; Chrysostomou et al. 1993, 1998; Ramsay et al. 1993). Several factors contribute to this (Sternberg and Neufeld 1999). Choosing a value for the ortho/para abundance ratio in place of the statistical weights of the respective levels, assuming an ortho/para abundance ratio in place of the spin degeneracy, \(g_r\), allows the column densities for a given vibrational level to lie along a smooth curve. The value adopted for Figs 9 and 10 and Tables 1 and 2 is 2.0. This value will be discussed in a subsequent paper. Since the transition from the lowest observable energy level originates from 510 K above the ground state, \(\text{H}_2\) emission is an indicator of highly energetic environments. The two dominant excitation processes in these interstellar regions are UV fluorescence from OB-type stars and shocks (Brand 1993). Figs 9 and 10 show clearly that the source of

### Table 2. Intensities measured in the brightest 31 pixels, i.e. area 1.23 by (1.23 x 31) arcsec

<table>
<thead>
<tr>
<th>Line</th>
<th>(\lambda) ((\mu)m)</th>
<th>Energy (K)</th>
<th>(A_j \times 10^{-7}) (s(^{-1}))</th>
<th>Intensity (\times 10^{-9}) (W m(^{-2}) sr(^{-1}))</th>
<th>Error (%)</th>
<th>(\log (N/g))</th>
<th>(\log (\text{cm}^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3–1</td>
<td>O(4)</td>
<td>1.4677</td>
<td>17387</td>
<td>2.859</td>
<td>10.86</td>
<td>12</td>
<td>13.85</td>
</tr>
<tr>
<td>5–3</td>
<td>Q(1)</td>
<td>1.4929</td>
<td>26735</td>
<td>11.716</td>
<td>19.12</td>
<td>9</td>
<td>13.41</td>
</tr>
<tr>
<td>6–4</td>
<td>S(1)</td>
<td>1.5016</td>
<td>31661</td>
<td>11.502</td>
<td>12.41</td>
<td>8</td>
<td>12.86</td>
</tr>
<tr>
<td>5–3</td>
<td>Q(3)</td>
<td>1.5056</td>
<td>27374</td>
<td>7.713</td>
<td>13.73</td>
<td>12</td>
<td>13.08</td>
</tr>
<tr>
<td>4–2</td>
<td>O(3)</td>
<td>1.5099</td>
<td>22079</td>
<td>7.724</td>
<td>19.62</td>
<td>9</td>
<td>13.61</td>
</tr>
<tr>
<td>5–3</td>
<td>Q(4)</td>
<td>1.5158</td>
<td>27878</td>
<td>7.435</td>
<td>4.28</td>
<td>22</td>
<td>12.79</td>
</tr>
<tr>
<td>3–1</td>
<td>O(5)</td>
<td>1.5220</td>
<td>17818</td>
<td>1.982</td>
<td>11.34</td>
<td>15</td>
<td>13.59</td>
</tr>
<tr>
<td>5–3</td>
<td>Q(5)</td>
<td>1.5286</td>
<td>28498</td>
<td>7.241</td>
<td>8.09</td>
<td>17</td>
<td>12.69</td>
</tr>
<tr>
<td>6–4</td>
<td>S(0)</td>
<td>1.5369</td>
<td>31303</td>
<td>8.308</td>
<td>6.13</td>
<td>22</td>
<td>13.16</td>
</tr>
<tr>
<td>4–2</td>
<td>O(4)</td>
<td>1.5635</td>
<td>22352</td>
<td>5.199</td>
<td>12.37</td>
<td>18</td>
<td>13.67</td>
</tr>
<tr>
<td>7–5</td>
<td>S(2)</td>
<td>1.5883</td>
<td>36050</td>
<td>13.252</td>
<td>4.39</td>
<td>31</td>
<td>12.57</td>
</tr>
<tr>
<td>11–8</td>
<td>S(1)</td>
<td>1.5915</td>
<td>47748</td>
<td>8.039</td>
<td>2.80</td>
<td>48</td>
<td>12.40</td>
</tr>
<tr>
<td>5–3</td>
<td>O(3)</td>
<td>1.6135</td>
<td>26735</td>
<td>11.216</td>
<td>15.87</td>
<td>11</td>
<td>13.38</td>
</tr>
<tr>
<td>6–4</td>
<td>Q(3)</td>
<td>1.6162</td>
<td>31661</td>
<td>9.211</td>
<td>8.99</td>
<td>15</td>
<td>12.85</td>
</tr>
<tr>
<td>7–5</td>
<td>S(1)</td>
<td>1.6205</td>
<td>35613</td>
<td>11.705</td>
<td>7.47</td>
<td>23</td>
<td>12.67</td>
</tr>
<tr>
<td>4–2</td>
<td>O(5)</td>
<td>1.6223</td>
<td>22759</td>
<td>3.694</td>
<td>9.11</td>
<td>19</td>
<td>13.26</td>
</tr>
<tr>
<td>6–4</td>
<td>Q(4)</td>
<td>1.6281</td>
<td>32132</td>
<td>8.841</td>
<td>3.38</td>
<td>50</td>
<td>12.64</td>
</tr>
<tr>
<td>6–4</td>
<td>Q(5)</td>
<td>1.6431</td>
<td>32711</td>
<td>8.565</td>
<td>8.22</td>
<td>21</td>
<td>12.66</td>
</tr>
<tr>
<td>5–3</td>
<td>O(4)</td>
<td>1.6718</td>
<td>26992</td>
<td>7.702</td>
<td>6.69</td>
<td>20</td>
<td>13.26</td>
</tr>
<tr>
<td>8–6</td>
<td>S(4)</td>
<td>1.6801</td>
<td>40695</td>
<td>11.023</td>
<td>3.23</td>
<td>52</td>
<td>12.38</td>
</tr>
<tr>
<td>1–0</td>
<td>O(8)</td>
<td>1.7147</td>
<td>14220</td>
<td>2.352</td>
<td>5.80</td>
<td>29</td>
<td>13.10</td>
</tr>
<tr>
<td>7–5</td>
<td>Q(1)</td>
<td>1.7288</td>
<td>35057</td>
<td>15.089</td>
<td>10.56</td>
<td>16</td>
<td>13.11</td>
</tr>
<tr>
<td>6–4</td>
<td>O(3)</td>
<td>1.7326</td>
<td>31063</td>
<td>14.094</td>
<td>16.08</td>
<td>10</td>
<td>13.32</td>
</tr>
<tr>
<td>1–0</td>
<td>O(7)</td>
<td>1.7480</td>
<td>12817</td>
<td>2.994</td>
<td>30.25</td>
<td>6</td>
<td>13.47</td>
</tr>
<tr>
<td>4–2</td>
<td>O(7)</td>
<td>1.7563</td>
<td>23955</td>
<td>1.892</td>
<td>2.51</td>
<td>67</td>
<td>12.83</td>
</tr>
<tr>
<td>8–6</td>
<td>S(1)</td>
<td>1.7639</td>
<td>39219</td>
<td>10.618</td>
<td>5.76</td>
<td>29</td>
<td>12.64</td>
</tr>
<tr>
<td>7–5</td>
<td>Q(5)</td>
<td>1.7784</td>
<td>36588</td>
<td>9.031</td>
<td>5.67</td>
<td>24</td>
<td>12.51</td>
</tr>
</tbody>
</table>
excitation is UV fluorescence, as opposed to thermal excitation which is characterized by data points from all vibrational levels lying on a single smooth curve (e.g. Brand et al. 1988). Evidence of collisional processes is not obvious and requires a comparison of the data with theoretical models.

4 SUMMARY

Infrared and far-red observations of the H$_2$ emission ridge 80 arcsec south of HD 37903 in the reflection nebula NGC 2023 have been presented. These have been carefully reduced to provide 87 H$_2$ line flux measurements. From these measurements a data set has been constructed of 66 column densities, each corresponding to a different rovibrational level of H$_2$. The wavelength range from which these transitions occur is sufficiently large to permit accurate estimates of the extinction value to the emission region.

These data will be combined with other published results to enable an analysis of physical conditions within the PDR to be presented in a subsequent paper.

ACKNOWLEDGMENTS

We thank the UKIRT staff of the Joint Astronomy Centre, Hawaii, the AAT staff of the Anglo-Australian Observatory, and in particular Tom Geballe and Jeremy Bailey, for assistance while these observations were being carried out. We are grateful to E. Roueff for supplying us with H$_2$ data in electronic form. PPARC are acknowledged for studentship funding for MSKM. PWJLB thanks the Universities of New South Wales, Sydney and Edinburgh, and the British Council, for financial assistance during this work.

Figure 9. AAT I-band data: column densities divided by degeneracy are plotted against excitation energy. An ortho/para abundance ratio of 2.0 is assumed.

Figure 10. CGS4 H-band data: column densities divided by degeneracy are plotted against excitation energy. An ortho/para abundance ratio of 2.0 is assumed.
REFERENCES

Horne K., 1985, PASP, 98, 609
Wright G. S., 1994, Exper. Astron., 3, 17

This paper has been typeset from a TEX/LATEX file prepared by the author.