Formation Pumping of Molecular Hydrogen in the Messier 17 Photodissociation Region

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ABSTRACT

We have imaged the emission from the near-infrared $v=1-0\ S(1)$, $1-0\ S(7)$, $2-1\ S(1)$ and $6-4\ O(3)$ lines of molecular hydrogen in the N– and SW–Bars of M 17, together with the hydrogen Br$\gamma$ and Br10 lines. This includes the first emission line image ever to be obtained of a line from the highly excited $v=6$ level of H$_2$. In both Bars, the H$_2$ emission is generally distributed in clumps along filamentary features. The 1–0 S(1) and 2–1 S(1) images have similar morphologies. Together with their relative line ratios, this supports a fluorescent origin for their emission, within a photodissociation region.

The SW–Bar contains a clumpy medium, but in the N–Bar the density is roughly constant. The 1–0 S(7) line image is also similar to the 1–0 S(1) image, but the 6–4 O(3) image is significantly different to it. Since the emission wavelengths of these two lines are similar (1.748 to 1.733 $\mu\text{m}$), this cannot be due to differential extinction between the $v=6$ and the $v=1$ lines. We attribute the difference to the pumping of newly formed H$_2$ into the $v=6$, or to a nearby, level. However, this also requires either a time-dependent photodissociation region (where molecule formation does not balance dissociation), rather than it to be in steady-state, and/or for the formation spectrum to vary with position in the source. If this interpretation of formation pumping of molecular hydrogen is correct, it is the first clear signature from this process to be seen.

Key words: stars: formation – ISM: molecules – infrared: ISM – molecular processes – ISM: H$\II$ regions – ISM: individual: M 17

1 INTRODUCTION

1.1 Messier 17

Messier 17 is one of the nearest regions of massive star formation to us, situated $\sim 1.3\ kpc$ away (Hanson, Howarth & Conti 1997). It is particularly notable for the bright H$\II$ region which attracted Messier’s attention (and also known as the Omega Nebula). Within it lies an obscured cluster of young stars. Thirteen OB stars have been spectroscopically identified (Hanson et al. 1997), all with between 4 and 15 magnitudes of extinction at optical wavelengths and estimated to be $\sim 10^6\ years$ old. The H$\II$ region is adjacent to a molecular cloud complex, in particular the core M 17 SW, which contains more than $10^4\ M_\odot$ of material (Lada 1976, Thronson & Lada 1983). Intense far–IR emission arises from the core, with a luminosity of $\sim 6 \times 10^6\ L_\odot$ (Harper et al. 1976, Wilson et al. 1979). While this originates from dust exposed to far–UV radiation, the core appears to be externally heated, by the stars that excite the H$\II$ region (Gatley et al. 1979), rather than internally. It forms a photodissociation region (PDR, Tielens & Hollenbach 1985). The method of excitation of the hydrogen molecules in it are the subject of this paper.

1.2 Molecular Hydrogen Observations in M 17

M 17 was first mapped in H$_2$ through the 2.12 $\mu\text{m}$ 1–0 S(1) line by Meadows (1986) and Gatley & Kaifu (1987). Their maps reveal two obvious regions of emission, a bar running across the north, and another running south to west. They are known as the ‘Northern Bar’ and the ‘South Western Bar’, respectively. They closely follow two emission ridges seen in radio continuum from 1.3 to 21 cm (Felli et al. 1984).
These bars are PDRs, interface regions between the ionized and the molecular gas. The Northern Bar also follows an optically visible bar of the H\textsc{i} region, suggesting that the extinction to it is relatively small. The South Western Bar, however, is optically obscured. PDR modelling of far-IR and sub-mm line emission features from the SW–Bar (Burton, Hollenbach & Tielens 1990, Meixner et al. 1992) indicates that it is a clumpy region, containing gas with a mix of densities, ranging from 10\(^6\) to 10\(^7\) cm\(^{-3}\), exposed to a far-UV radiation field of \(\sim 10^4\) times the average interstellar radiation field.

Low spatial resolution (20 arcsec beam) near-IR spectroscopy of the 1–0 and 2–1 S(1) \(\text{H}_2\) lines (Tanaka et al. 1989) in the N–Bar found a line ratio of \(\sim 2\). This is the ratio expected if the excitation is via a fluorescence cascade through the vibrational-rotational levels of the ground electronic state (Black & Dalgarno 1976). The molecule is first excited by far-UV photons to an excited electronic level, from which it decays. Chrysostomou et al. (1992, 1993) imaged the N–Bar with arcsecond spatial resolution in the \(\text{H}_2\) 1–0 S(1) line, as well as in the 3.29 \(\mu\)m PAH emission feature and the hydrogen Br\text{\tiny{y}} line at 2.17 \(\mu\)m. They also obtained long slit spectroscopy across the N–Bar from 2.0–2.5 \(\mu\)m, measuring 16 lines of \(\text{H}_2\), as well as several H\text{\tiny{ii}} region emission lines. The spatial coincidence found for the PAH and \(\text{H}_2\) emission features confirmed the fluorescent origin, and also suggested that most of the gas had density \(\gtrsim 10^5\) cm\(^{-3}\). They found the 1–0/2–1 S(1) ratio to be \(\sim 3\), and to be constant along the 60 arcsec long slit. This not only suggests that the \(\text{H}_2\) is slightly thermalised (i.e. the density is about the critical density, \(\sim 10^5\) cm\(^{-3}\)), but that the physical conditions along the N–Bar are constant.

1.3 Molecular Hydrogen Excitation in PDRs

In dense PDRs, with a strong far-UV radiation field, self-shielding can bring the \(\text{H}/\text{H}_2\) dissociation front to optical depths \(A_\lambda < 1\) mag from the ionized surface of the cloud. Here the temperature can reach 1,000–2,000 K, allowing the \(v=1\) level of \(\text{H}_2\) to be thermalised. \(\text{H}_2\) line ratios, for instance the 1–0/2–1 S(1) ratio, then increase from the pure fluorescent value of 2, towards the thermal value of 10 observed in shocks and in gas at \(\sim 2000\) K (see Sternberg & Dalgarno 1989, Burton, Hollenbach & Tielens 1990). The actual line ratio depends on the density of the gas. If this is not constant, then the ratio will likely vary with position in a source. However calculating its value depends on an accurate knowledge of the collisional excitation rate coefficients for \(\text{H}_2\), which are poorly known. Hence the quantitative application of “collisional fluorescence” models to the interpretation of \(\text{H}_2\) lines ratios in PDRs requires some care.

A component of the fluorescent emission from \(\text{H}_2\) must arise due to the formation of the hydrogen molecules themselves. For photo-excitation of \(\text{H}_2\) molecules by far-UV photons, approximately 15% lead to dissociation. However the hydrogen molecules can be reformed, through the recombination of two hydrogen atoms on the surfaces of dust grains (Hollenbach & Salpeter 1971). In the steady state, the rate of formation of \(\text{H}_2\) molecules balances its rate of photodissociation. The 4.5 eV bond energy of \(\text{H}_2\) is released on formation. Some of this is used in escaping from the surface of the dust grain, some goes into translational kinetic energy in the molecule, and the rest goes into internal energy. The new molecules can then emerge in an excited vibrational-rotational state, from which radiative decay will occur. Thus a formation component to the \(\text{H}_2\) spectrum is expected. However, the signature of this spectrum is unclear.

As Black & Dalgarno (1976) first realised, when calculating the infrared spectrum of fluorescent \(\text{H}_2\), the contribution from molecule formation may be important. In their original model they assumed equipartition of the binding energy released on formation. They divided this equally between the internal energy of the molecule, its translational energy on escape from the grain surface, and the internal energy imparted to the grain lattice. They further assumed that the 1.5 eV provided as internal energy to the molecule was spread with a Boltzmann distribution through the vibrational-rotational levels. However, other assumptions are possible. For instance, Hunter & Watson (1978) argue that \(\text{H}_2\) molecules are released in rotationally hot, vibrationally cold states (i.e. high-\(J \geq 7\), low-\(v\)). A model by Duley & Williams (1986), on the other hand, although agreeing that the molecules should form hot, argued that they would appear in just the opposite combination of states (i.e. low-\(J\), high-\(v\), with \(v=6\) likely). Le Bourlot et al. (1995) have investigated the infrared spectrum produced for pure formation pumping of \(\text{H}_2\), under a variety of formation models. For instance, as might be expected, the intensities of \(v=6\) lines are found to be considerably greater under the Duley & Williams (1986) model than in other models. However, since this model does not include the fluorescent cascade component to the emission, which will generally dominate the intensity of the \(\text{H}_2\) lines, it is hard to use it to undertake a quantitative comparison with data.

1.4 Previous Reports of the Detection of Formation Pumping for \(\text{H}_2\)

There have been few reports made of the signature for \(\text{H}_2\) formation being observed in a spectrum. Wagenblast (1992) considers UV absorption spectra of three nearby diffuse clouds, along lines of sight to background stars. He finds that the populations in the excited, pure-rotational levels, \(v=0, J=5, 6 & 7\), along the sight lines, cannot be produced by UV or thermal excitation. Assuming that molecule formation takes place in two adjacent rotational levels within a particular vibrational state (one for ortho-\(\text{H}_2\), or odd-\(J\), and the other for para-\(\text{H}_2\), or even-\(J\)), he calculates the possible pairings that could account for the observed ratios of the three lines. He found that \(\text{H}_2\) would need to be formed in a rotationally hot state (\(J \geq 7\), but with a range of vibrational states possible, up to \(v=11\)). Federman et al. (1995) explore this further with additional absorption measurements from the \(v=3\) level in the source \(\zeta\) Oph, though do not find any fit to the data particularly satisfactory.

Mouri & Taniguchi (1995) consider the 1.5–2.5 \(\mu\)m spectrum of the starburst galaxy NGC 6240, where a number of \(\text{H}_2\) lines are evident. Based on the relative strengths of the 1–0 S(7) and S(9) lines, compared to the 1–0 S(1) line, they argue that formation pumping, via associative detachment of H and H\text{\tiny{ii}} to form \(\text{H}_2\), provides an important contribution to the line intensity. However the data on which this is based have low spectral resolution, and suffers from blending. Moreover, the data are fit with a model which contains
several components to the 1–0 S(1) line intensity; formation (10%), fluorescence (20%) and thermal excitation (70%). In addition, the \( v=6–4 \) Q(1) line at 1.64 \( \mu m \), observed by Elston & Maloney (1990) in this source, and arising from the same level as the 6–4 O(3) line which we report on in this paper, is weak compared to the 1–0 S(1) line, less than 10% its intensity. It has low signal to noise in the spectrum. Hence, claims for a formation signature in the data need to be regarded with caution.

Measurements of over 30 high-excitation H\(_2\) lines in the reflection nebula NGC 2023 by Burton et al. (1992) lead these authors to speculate on whether there was a formation component to the emission from several lines from the \( v=4 \) level. This was based on an excess in the level column density distribution for these lines compared to expectations for pure fluorescence emission (and see also McCartney et al. 1999 for an extension to \( v=6 \) in this source, for which the excess may still be apparent). However, the signal to noise is not sufficient to be certain that the excess is real, and moreover, might be mistaken for ortho-to-para ratio variations between lines in different vibrational levels.

This paper presents images of emission lines from the \( v=1 \), 2 and 6 levels in M17, as well as in the hydrogen Br\( \gamma \) line. This includes the first map ever obtained of an H\(_2\) emission line from the \( v=6 \) level. While the bulk of the H\(_2\) emission is clearly fluorescent in origin, we argue, based on the different morphology for the \( v=6–4 \) O(3) line to the lower excitation lines, that formation pumping of H\(_2\) provides a significant component to its flux.

2 OBSERVATIONS AND DATA REDUCTION

Two fields in the source Messier 17 were observed using the IRIS 1–2.5 \( \mu m \) camera, in conjunction with the University of New South Wales Infrared Fabry-Pérot etalon (UNSWIRF, Ryder et al. 1998), on the 3.9-m Anglo-Australian Telescope (AAT). The data were obtained on 1997 July 21–23. The fields were chosen to centre on the H\(_2\) emission in the northern (N) and south-western (SW) ionization bars of M 17, at \( 18^h20^m42.8^s, -16^\circ8'23" \) and \( 18^h20^m25.3^s, -16^\circ11'27" \) (J2000), respectively. These are shown in Fig. 1 overlaid on a 3-colour near-IR image of M 17 (1–2.5 \( \mu m \)) obtained by Lada et al. (1991). This image clearly shows the two ionization bars, with blue indicating the ionized gas (through Paschen lines of hydrogen in the 1.25 \( \mu m \) band) and red mostly indicating the photodissociation region (PDR, through fluorescently-excited H\(_2\) lines in the 2.2 \( \mu m \) band).

The UNSWIRF etalon has a FWHM spectral resolution of \( \sim 75 \) km s\(^{-1}\), a pixel size of 0.77 arcsec and a 100 arcsec circular field of view. It is scanned through a spectral line of interest in order to obtain an emission line image with minimal contamination from any continuum radiation present in a source.

The H\(_2\) 1–0 S(1) (2.1218 \( \mu m \)), 2–1 S(1) (2.2233 \( \mu m \)), 1–0 S(7) (1.7480 \( \mu m \)) and 6–4 O(3) (1.7326 \( \mu m \)) lines, and the hydrogen Br\( \gamma \) (\( n=7–4 \), 2.1661 \( \mu m \)) and Br\( \alpha \) (\( n=10–8 \), 1.7367 \( \mu m \)) lines were imaged in the N field, and just the 2 \( \mu m \)-band lines in the SW field. Each of the three 2 \( \mu m \) lines was imaged, using appropriate 1% width blocking filters, by stepping the etalon through the relevant plate spacings for the line of interest. All three 1.7 \( \mu m \) lines were imaged with the same 1.5% width blocking filter. For the weaker 6–4 O(3) line, which had never been imaged before, the spectral scan was defined to also include the nearby Br\( \alpha \) line. The hydrogen line provided a wavelength reference point to ensure the correct plate spacing was used for the 6–4 O(3) line.

The observing sequence with UNSWIRF included 3 on-line settings for the 2 \( \mu m \) lines, and 5 on-line settings for the 1.7 \( \mu m \) lines, equally spaced in 39 km s\(^{-1}\) steps about the respective line centres. An ‘off-line’ setting was chosen to provide continuum subtraction. Sky frames were also taken for each etalon spacing. An integration time of two minutes was used for each setting at 2 \( \mu m \), and five minutes at 1.7 \( \mu m \). The corresponding sky frames were taken immediately after each source frame for each separate Fabry-Pérot etalon setting (and located 5 arcmin N for the N-field and 5 arcmin W for the SW-field). One such sequence of frames was taken for the 1–0 S(1) and Br\( \gamma \) lines, four for the 2–1 S(1) line (two in the SW field) and two for the 1.7 \( \mu m \) lines. Each repeated sequence was centred on a slightly different source position, to minimise the effect of any bad pixels.

The stars BS7330 (K=4.97 mag) and BS6748 (K=4.57 mag) were used as flux standards, and were imaged at each of the etalon spacings. A diffused dome lamp provided a flat field for each etalon spacing, and an arc lamp was scanned through a free spectral range in order to wavelength calibrate the Fabry-Pérot etalon response for each pixel of the array.

Data reduction was through a custom software package using IRAF\(^\dagger\). Frames are linearised, flat-fielded using a dome flat at the appropriate plate setting, sky-subtracted, shifted to align stars in each frame, smoothed and the off-line frame subtracted from each on-line frame (having been appropriately scaled to minimise residuals from the subtraction process). Stacking of the frames yields a data cube, which is then fitted pixel-by-pixel with the instrumental profile (a Lorentzian) to yield a line image. Results from different sequences on the same line were then coadded. The absolute accuracy in flux calibration is typically around 30% for each image, and line ratios determined from them can thus have a (constant) scaling error of up to a factor of two. However, the error in relative line ratios determined between any two pixels is much smaller than this, depending only on the S/N each line has been measured with, and not on the accuracy of the absolute calibration.

The line centre for each pixel is determined from the plate spacing found for peak of the fitted profile, with an accuracy of \( \sim 10 \) km s\(^{-1}\) (depending on the intensity). Within these errors, the emission velocity for each line across the fields was found to be the same, as expected for a photodissociation region, where gas motions are very much less than the spectral resolution of the data.

3 RESULTS

3.1 Northern Bar

\(^\dagger\) Image Reduction and Analysis Facility (www.iraf.noao.edu)
are the 1–0 S(1) (2.1218 µm), 2–1 S(1) (2.2333 µm), 6–4 O(3) (1.7326 µm) and 1–0 S(7) (1.7480 µm) transitions. Images are overlaid with contours of the same lines. Contour levels are as follows: for the 1–0 and 2–1 S(1) lines, starting from, and in steps of 3 × 10−16 erg s−1 cm−2 arcsec−2; for the 6–4 O(3) line, starting from, and in steps of 0.5 × 10−16 erg s−1 cm−2 arcsec−2; for the 1–0 S(7) line, starting from, and in steps of 1 × 10−16 erg s−1 cm−2 arcsec−2.

3.1.1 H2 1–0 S(1), 1–0 S(7) and 2–1 S(1) Lines

Fig. 2 shows images of the H2 1–0 S(1), 2–1 S(1), 6–4 O(3) and 1–0 S(7) lines from the N field. Line fluxes and line ratios for selected regions are shown in Table 1. Fig. 3 compares, for the N field, the distribution of the H2 1–0 S(1) line (in greyscale) to that of the 2–1 S(1), 6–4 O(3), 1–0 S(7) and H Brγ lines (in contours), respectively. The ionization front between the HII and H2 emitting gas can be seen, though since foreground ionized gas envelops the whole region, it renders its location hard to discern.

Giving regard to the 30% error in absolute calibration, discussed in §4, the intensity of the 1–0 S(1) line at the peak, 5 × 10−13 erg s−1 cm−2 in an 18 × 15 arcsec aperture, compares reasonably with the flux measured in the N–Bar by both Tanaka et al. (1989) (3 × 10−13 erg s−1 cm−2 in a 20 arcsec beam) and by Chrysostomou et al. (1993) (3.5 × 10−13 erg s−1 cm−2 in long slit with 180 arcsec2 effective area). The total 1–0 S(1) line emission from the N–Bar field is 5.3 × 10−12 erg s−1 cm−2, and the brightest emission peaks at 3.2 × 10−12 erg s−1 cm−2 arcsec−2 at 18h20m42.3s, −16°08′51″ (J2000).

The overall morphology of the line emission is one of clumpy filaments, with two roughly parallel features running SE–NW across the field. They are embedded in diffuse H2 emission, extending to the NE of the field. The morphology is similar in the 1–0 S(1), 2–1 S(1) and 1–0 S(7) line images. This indicates that the 1–0/2–1 S(1) ratio is reasonably constant across the field.

The line ratio variations are quantified in Table 1. The 1–0 S(1)/2–1 S(1) ratio varies from 1.3 to 2.1, with a mean of 1.6. The 1–0 S(1)/1–0 S(7) ratio varies from 3.9 to 4.9, with a mean of 4.0.

Chrysostomou et al. (1993) also found little variation in the 1–0 S(1)/2–1 S(1) ratio, with a value of 3 ± 0.5 over most of the region they observed. Tanaka et al. (1989) determined 1.9 for this ratio. Our own determination is 1.6. However, given the uncertainty in absolute calibration for measurements made through Fabry-Pérot etalons, these determinations are consistent with one another. The value of 3 is more likely to be correct, though, since measurements through a long slit have better relative accuracy for line ratio determinations. This suggests our 1–0 S(1)/2–1 S(1) line ratios might need to be scaled by ~ 1.8 for the N–Bar.

The similarity of the 1–0 S(1) and 1–0 S(7) line images indicates that any differential extinction between their emitting wavelengths, 1.75 and 2.12 µm, must be uniform (or minimal). This is consistent with the estimate of the extinction of 0.05 mag at 2.2 µm found by Chrysostomou et al. (1993), based on hydrogen recombination lines at 1.09 and 2.16 µm. For this value of extinction, the differential extinction between 1.7 and 2.1 µm is indeed negligible.

3.1.2 H2 v=6–4 O(3) Line

For the v=6–4 O(3) line, while the emission clearly arises from the same region as the lower excitation lines, its distribution within that region is quite different. The line is considerably brighter in the NE of the two emitting filaments, contrary to what is seen in the v=1 and v=2 line images. The number of distinct clumps is also greater in the 6–4 O(3) image.

Since the v=6–4 O(3) line is emitted at a similar frequency to the 1–0 S(7) line there will not be any differential extinction between these two lines. Thus, the difference in morphology between the 6–4 O(3) line and the 1–0 S(1) line reflects differences in their excitation. It is not the result of differential extinction between the emitting wavelengths of these two lines.

The 1–0 S(1)/6–4 O(3) ratio varies from 5 to 23 in the N–Bar, with a mean value of 11 (see Table 1). This is a factor of two variation from the mean ratio, compared to less than 30% variation measured for the ratio of the 1–0 S(7) and 2–1 S(1) lines with the 1–0 S(1) line.

3.2 South Western Bar

In Fig. 3 are shown the H2 1–0 and 2–1 S(1) lines and the H Brγ line for the SW field, together with an overlay of the Brγ line on the 1–0 S(1) line. Line fluxes are again listed in Table 1. The H Br10 line is not shown, but is similar to the Brγ line in appearance. Again the H2 emission is distributed along clumpy filaments, and (giving regard to the lower S/N in the v=2 image) the v=1 and 2 lines show similar morphologies. A clear ionization front is evident between the Brγ and 1–0 S(1) images, with the brightest emission filaments running parallel and separated by ~ 5 arcsec.

The total 1–0 S(1) line flux from the SW field is 2.6 × 10−12 erg s−1 cm−2. The flux peaks at 1.9 × 10−15 erg s−1 cm−2 arcsec−2 at 18h20m23.1s, −16°11′16″ (J2000). Both these fluxes are about half the correspond-
ing values in the N–Bar. This is probably mostly due to the extra extinction in the optically obscured SW–Bar. The 1–0 S(1)/2–1 S(1) line ratio varies between 3 and 8, with a mean value of 4.4. This is both higher than in the N–Bar, and shows significantly more variation with position. This line ratio cannot be considered as constant over the field, unlike in the N–Bar.

4 DISCUSSION

4.1 PDR Emission and Gas Density

As has been discussed in several previous papers, the molecular hydrogen line emission in M17 is dominated by UV fluorescence (e.g. Tanaka et al. 1989, Chrysostomou et al. 1992, Chrysostomou et al. 1993). This is evident through the morphology, its proximity to the ionization front of an HII region, the similarity to UV–excited 3.3 µm PAH emission, and through the measurements made of H2 vibrational line ratios. Our data confirm this result. In particular, the strength of the v=2–1 S(1) line compared to the v=1–0 S(1) line is indicative of a non-thermal excitation method such as UV fluorescence (e.g. Black & Dalgarno 1976, Black & van Dishoeck 1987).

In the SW–Bar the line ratio rises above the pure fluorescent value, indicating that the density of some of the gas there is greater than critical (~10^5–10^6 cm^{-2}, depending on uncertain values for the H2 collisional excitation rates). In such cases collisions can re-populate the v=1 level so that the ratio of the v=1–0 to the v=2–1 S(1) lines can appear thermal (i.e. ~10, see Sternberg & Dalgarno 1989, Burton, Hollenbach & Tielens 1990). However when such “collisonal fluorescence” is seen, density variations within the emitting region invariably give rise to significant variations in the value of this line ratio within the source (see Ryder et al. 1998, Allen et al. 1999). Density variations must occur in the SW–Bar of M17 too.

However the bulk of the gas in the SW–Bar must have density no more than critical. This can be determined from the separation between the ionization front and the excited H2 there, ~5 arcsec. Assuming this corresponds to an extinction of A_v ~ 1 mag (i.e. N ~ 10^{21} H2 molecules cm^{-2}), it implies that the average H2 number density is n ~ 1 x 10^4 cm^{-3} in the SW–Bar. Given the high density component that is also there, the medium must therefore be a clumpy one.

In the N–Bar we will take the line ratio to be 3, as determined by Chrysostomou et al. (1993). This is only a little higher than the pure fluorescent value, and suggests that the density here is about equal to the critical density. The constancy of the ratio across the N–Bar also suggests that there is also little variation in the density. This is in contrast to the clumpy SW–Bar.

4.2 Molecular Hydrogen Formation Pumping

The most interesting result from this work is the v=6–4 O(3) emission line image of the N–bar, shown in Fig. 2. This is the first time an image in such a high-excitation line of H2, 31,000 K above ground state, has been obtained. While the line arises from the same regions as the v=1 and v=2 lines of H2, its distribution within them is clearly different.

Since all the lines arise from ortho (odd–J) states, the difference between them is also unlikely to result from ortho-to-para ratio variations, unless these both vary with position in the source, as well as between vibrational levels.

It is also hard to see how the 6–4 O(3) line could have been mis-identified. It cannot be a line emitted from the HII region due to the completely different morphology from the hydrogen lines. Since the line is emitted from the same regions as the lower excitation H2 lines it also suggests that it is a PDR line, and not from the HII region. Moreover, the nearby H Br10 line provided a wavelength reference point for scanning the Fabry–Pérot etalon across the correct plate spacings for the 6–4 O(3) line.

The v=6–4 O(3) line emission almost certainly arises from a region where the H2 emission is dominated by UV–fluorescence. It cannot be shocked or X–ray excited since the high energy of the (v,J) = (6,1) upper level (31,000 K) would not be significantly populated by thermal means. The 6–4 O(3) line would be ~10^{-4} of the strength of the 1–0 S(1) line for thermal excitation at 2000 K, considerably weaker than the nearby 1–0 S(7) line, which would be about 10% of the 1–0 S(1) line strength. In fluorescent models, however,
the v=6–4 O(3) line intensity is significant; for instance in Black & van Dishoeck’s Model 14 it is 31% of the value of the 1–0 S(1) line. In the same model the 2–1 S(1) line is 56% the strength, and the 1–0 S(7) line 18%, of the 1–0 S(1) line intensity (neglecting any differential extinction between the emitting wavelengths). This is broadly consistent with the data, for which the mean fluxes of the 2–1 S(1), 1–0 S(7) and 6–4 O(3) lines are \( \sim 60\% \), 25\% \( \) and 10\% of the 1–0 S(1) line, respectively. However the specific predictions for the strength of the lines depend upon an additional excitation mechanism to the fluorescent cascade, formation pumping.

For every \( \text{H}_2 \) molecule that is fluoroescently excited, 15\% lead to photodissociation (e.g. Draine & Bertoldi 1996). In steady state PDR models, molecule destruction is balanced by molecule formation, which is believed to occur on grain surfaces (e.g. Hollenbach & Salpeter 1971). The newly formed \( \text{H}_2 \) molecules are released in an excited vibrational-rotational state. However, there is little hard evidence to suggest in what state, or distribution of states, this might be. Black & van Dishoeck (1987) consider three possible formation models. Their ‘standard’ Model 14 assumes that 1.5\,eV of the binding energy is distributed in a Boltzmann distribution through the energy levels (after Black & Dalgarno 1976). A second model assumes that the new molecules all appear in \( v=14, J=0 \) or 1 (after Hunter & Watson 1978). The third formation model is based on a treatment of \( \text{H}_2 \) catalysis by Duley & Williams (1986) which predicts the molecules are ejected into the \( v=6 \) level. Naturally, there are significant differences in the predictions of the intensities for lines from \( v=6 \) between the first two and the third formation model. Depending on the formation temperature of the molecule, \( v=6 \) lines are predicted to be up to a factor \( \sim 3 \) times brighter in the third than in the first formation model. This suggests that the 1–0 S(1)/6–4 O(3) ratio may fall from \( \sim 10 \) to \( \sim 3 \) in Black & van Dishoeck’s (1987) Model 14, if it were to be modified so that \( \text{H}_2 \) formation occurred in \( v=6 \), rather than into a Boltzmann distribution.

We believe that formation pumping into \( v=6 \), or to a nearby level, provides the best explanation for the difference in the images between the 6–4 O(3) line and the lower excitation lines. However, it cannot simply be due to the additional component that formation pumping adds to the intensity of a line, for that would not result in a different morphology for the line. Either the rate at which formation is occurring must vary with position, or the formation spectrum itself is varying with position (for instance, due to a varying formation temperature), across the N–Bar of M 17.

In the Duley & Williams model, about 1.5\,eV of the 4.5\,eV bond energy released is assumed to remain with the \( \text{H}_2 \) molecule, as it is ejected from the surface of the dust grain where it formed. This puts it into an excited rotational-vibrational state, namely \( v \sim 6 \). The actual formation process depends intimately on the nature of the surface of the dust grains. In their 1986 paper Duley & Williams considered the surfaces to be highly defected silicates, to which the molecule is moderately strongly bound. A later paper (Duley & Williams 1993) further considers \( \text{H}_2 \) formation on amorphous \( \text{H}_2\text{O} \) ice (where it is weakly bound) and on aromatic carbon molecules (e.g. PAHs or HACs, where it is strongly bound). If the former occurs, they suggest that the \( \text{H}_2 \) will be released in highly excited states (i.e. the binding energy virtually all goes into internal energy of the \( \text{H}_2 \) molecule, so it ends up, perhaps, in \( v=13 \)). In the latter case, most of the binding energy would be distributed through the many degrees of freedom of the aromatic molecule, leaving the \( \text{H}_2 \) in a low-excitation state. Clearly, the observations in M 17 support the silicate grains model for that source over the other two grain models, since the excess appears to be in \( v=6 \).

The PDR models discussed above were steady state models, where the dissociation front is stationary. In them, the photodissociation rate of hydrogen molecules by far–UV radiation is balanced by their formation rate on grains. This need not be the case. The timescale for the \( \text{H}_2/\text{H} \) dissociation front to reach equilibrium, \( t_{\text{eq}} \sim 5 \times 10^5/\text{n years} \), can be long compared to variations in the radiation field (for instance, soon after a star switches on) (Hollenbach & Natta 1995). In M 17, the data constrain \( t_{\text{eq}} \) to be less than \( \sim 10^6 \) years. The exposure of previously shielded \( \text{H}_2 \) molecules to the far–UV radiation field, as the dissociation front moves further into a molecular cloud, increases the column of fluoresced gas. Thus, the \( \text{H}_2 \) line intensities rise from their steady state values. The 1–0 S(1) line intensity can be elevated by an order of magnitude (Hollenbach & Natta 1995). Moreover, since this emission is dominated by pure fluorescence (collisions can only play a minor role in redistributing the level populations), the 1–0/2–1 S(1) ratio will be \( \sim 2 \). Any thermal contribution to the 1–0 S(1) line has been minimised.

During this time the rate of molecule destruction must exceed that of formation. Thus the relative proportion of the formation component to the fluorescent \( \text{H}_2 \) line intensities will be reduced. We now consider whether this explanation can be applied towards explaining the 6–4 O(3) line emission from the N–Bar of M 17. In it, the line is brighter in the NE of the two emission filaments, the one furthest away (at least in projected distance) from the ionizing stars in the H\beta region. Our hypothesis is that a formation component contributes to the 6–4 O(3) line intensity. This would imply that, in the weaker of the two filaments, a smaller proportion of the emission has been produced by formation pumping, compared to that produced by pure fluorescence, than in the brighter of the filaments. Thus, this suggests that the SW of the two filaments contains a non-steady state photodissociation region, where the dissociation front is moving rapidly into the molecular cloud.

We can apply this interpretation to provide a rough estimate of the fraction of the 6–4 O(3) line intensity that derives directly from \( \text{H}_2 \) formation in a steady state PDR. We assume that when the 1–0 S(1)/6–4 O(3) ratio is at its largest (i.e. \( 23 \)), then the UV cascade dominates its excitation. We also assume that when it is at its smallest value (i.e. 5) this represents the steady state PDR. This then yields a formation component that is \( \sim 80\% \) of the total 6–4 O(3) line intensity in the steady state, the remaining \( \sim 20\% \) coming from the fluorescent cascade. This is obviously a crude estimate. Without further data on high excitation \( \text{H}_2 \) lines we cannot say more about the formation spectrum of \( \text{H}_2 \).
5 SUMMARY

The molecular hydrogen line emission from the N- and SW-Bars of M17 clearly is fluorescently excited, from inside a photodissociation region. The N-Bar has approximately constant density, whereas the SW-Bar contains a clumpy molecular medium. However, the different distribution of the emission from the v=6–4 O(3) line, compared to that of the lower excitation lines from the v=1 and 2 levels, indicates that another mechanism is significant for its excitation. We argue that this is formation pumping, newly formed molecules being released from grain surfaces in an excited state, at or near the v=6 level. This therefore resembles the suggestion put forward by Duley & Williams (1986) for H$_2$ formation on the surface of highly defected silicate grains, where the molecules are released with $\sim$1.5 eV of the 4.5 eV molecule binding energy. However, time-dependent PDR models are also needed in order to quantitatively model such emission. This is because the proportion of the H$_2$ line emission that has been produced by formation pumping, in comparison to fluorescence, probably varies with position in the source.

If this hypothesis is correct it may be tested by imaging in other highly excited emission lines. For instance, the v=6–4 Q(1) line at 1.6011 $\mu$m, the 5–3 O(3) line at 1.6131 $\mu$m, the 7–5 S(1) line at 1.6201 $\mu$m and the 7–5 Q(1) line at 1.7283 $\mu$m, are all emitted from nearby levels and in the same atmospheric window. The v=6 and v=5 lines would likely look similar, but, depending on whether any H$_2$ is pumped into v=7 on formation, the distribution of the latter two lines may look closer to that of the lower excitation v=1 lines. Imaging Fabry-Pérot etalons are suitable instruments for these observations, because of their high spectral resolution, needed to separate out other lines in the window, and because they enable the spatial morphology to be examined. Long-slit spectroscopy, again at high spectral resolution, across the emission bars, would permit further examination of the merits of the formation hypothesis. It would help determine which lines have a formation component to their emission fluxes. Such data are needed to provide constraints on what the H$_2$ formation spectrum actually is.

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Table 1. Molecular hydrogen line fluxes in selected regions of the N–Bar and the SW–Bar of M17. The regions are numbered and shown in Fig. 1 and Fig. 2, respectively. The coordinates (in J2000) of the brightest emission in each region is listed in columns 2–3. The aperture size, in arcsec, is indicated in column 4. In columns 5–8 line fluxes, in \(10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\), are listed for the 1–0 S(1), 2–1 S(1), 1–0 S(7) and 6–4 O(3) lines. Line ratios for 1–0 S(1)/2–1 S(1), 1–0 S(1)/1–0 S(7) and 1–0 S(1)/6–4 O(3) are listed in columns 9–11. At the end of the tabulation for each Bar, the line fluxes and ratios for the whole field are also listed.

| Region          | RA 18\(^h\)20\(^m\) | Dec ° | Aperture arcsec | 1–0 S(1) \(\times 10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\) | 2–1 S(1) \(\times 10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\) | 1–0 S(7) \(\times 10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\) | 6–4 O(3) \(\times 10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\) | 1–0 S(1) / 2–1 S(1) | 1–0 S(1) / 1–0 S(7) | 1–0 S(1) / 6–4 O(3) |
|-----------------|-------------------|-------|----------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|-----------------|-----------------|-----------------|
| Northern Bar     |                   |       |                |                                 |                                 |                                 |                                 |                 |                 |                 |
| 1               | 43.6\(^a\) 08°30\(^m\) | 18 × 15 | 48.4 ± 0.6 | 29.5 ± 0.6 | 12.1 ± 0.2 | 3.4 ± 0.1 | 1.6 ± 0.1 | 4.0 ± 0.1 | 14.1 ± 0.5 |
| 2               | 41.4\(^a\) 08°35\(^m\) | 18 × 17 | 30.1 ± 0.5 | 15.6 ± 0.5 | 7.7 ± 0.2 | 1.8 ± 0.1 | 1.9 ± 0.1 | 3.9 ± 0.2 | 17.2 ± 0.9 |
| 3               | 42.3\(^a\) 08°51\(^m\) | 17 × 13 | 24.5 ± 0.4 | 11.8 ± 0.4 | 6.1 ± 0.1 | 1.1 ± 0.1 | 2.1 ± 0.1 | 4.0 ± 0.2 | 22.7 ± 1.2 |
| 4               | 42.8\(^a\) 07°50\(^m\) | 9 × 12  | 12.5 ± 0.4 | 8.4 ± 0.4 | 3.0 ± 0.1 | 1.1 ± 0.1 | 1.5 ± 0.1 | 4.1 ± 0.3 | 11 ± 1     |
| 5               | 45.3\(^a\) 08°33\(^m\) | 15 × 16 | 25.1 ± 0.6 | 19.2 ± 0.6 | 6.2 ± 0.2 | 3.8 ± 0.1 | 1.3 ± 0.1 | 4.1 ± 0.2 | 6.6 ± 0.4 |
| 6               | 43.6\(^a\) 07°51\(^m\) | 12 × 15 | 15.4 ± 0.5 | 11.4 ± 0.5 | 3.2 ± 0.2 | 3.1 ± 0.1 | 1.4 ± 0.1 | 4.9 ± 0.5 | 5.0 ± 0.4 |
| Total           | 83 × 85           | 528 ± 3 | 335 ± 3 | 132 ± 1 | 49 ± 0.5 | 1.6 ± 0.1 | 4.0 ± 0.1 | 10.9 ± 0.2 |
| South Western Bar|                   |       |                |                                 |                                 |                                 |                                 |                 |                 |                 |
| 1               | 24.9\(^a\) 11°37\(^m\) | 15 × 19 | 34.8 ± 0.7 | 4.4 ± 0.7 | 7.9 ± 1.4 |
| 2               | 26.3\(^a\) 11°04\(^m\) | 14 × 13 | 12.6 ± 0.5 | 4.0 ± 0.5 | 3.1 ± 0.5 |
| 3               | 23.1\(^a\) 11°10\(^m\) | 11 × 12 | 17.3 ± 0.4 | 6.1 ± 0.4 | 2.8 ± 0.3 |
| 4               | 23.4\(^a\) 12°00\(^m\) | 15 × 21 | 19.9 ± 0.7 | 3.9 ± 0.7 | 5 ± 1     |
| Total           | 66 × 84           | 264 ± 3 | 61 ± 3   | 4.4 ± 0.3 |
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