# Evidence of chromospheric molecular hydrogen emission in an IRIS flare

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**(Mulay S. M., Fletcher L., 2021, MNRAS, 504, 2842)**

# Overview

- Formation of molecular hydrogen $H_2$ emission
- Chromospheric $H_2$ emission observed in an IRIS flare
- Summary
- Future research plan

# Emission from molecular hydrogen $H_2$ in solar atmosphere

## $H_2$ emission

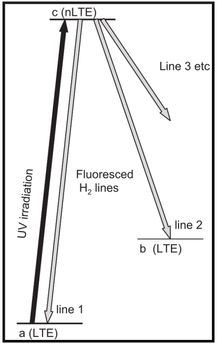
- Formation temperature = 4200 K (Innes 2008)
- Provides information about the Temperature Minimum Region (TMR)
- Formed by **photo-excitation (fluorescence) by ultraviolet (UV) radiation** from the transition region.

## Question?

- Can bright UV line radiation that excites $H_2$ fluorescence penetrate down from the tenuous hotter regions to these cooler layers?

## Answer

- Yes. UV photons travel down to excite $H_2$
- **Jaeggli *et al.* 2018** - **Non-LTE models**
- studied conditions under which $H_2$ emission can originate.




**Jaeggli *et al.* 2018**
Transitions between different vibrational states of the molecule

## Results from non-LTE model

- Temperature stratification plays the dominant role in determining the population densities of $H_2$, which forms in greatest abundance near the continuum photosphere.

- Opacity due to the photoionization of Si and other neutrals determines the depth to which UV radiation can penetrate to excite the $H_2$.

- The majority of $H_2$ emission forms in a narrow region, at about 650 km above the photosphere in standard one-dimensional (1D) models of the quiet Sun.

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# Details of $H_2$ emission lines observed by IRIS in C II and Si IV windows

| (Column 1) | (Column 2) | (Column 3) | (Column 4) | (Column 5) | (Column 6) | (Column 7) | (Column 8) |
|---|---|---|---|---|---|---|---|
| **$H_2$ $\lambda$ (Å)** | **Transition ($v'$ - $v''$)** | **Branch ($\Delta J = \pm 1$)** | **Exciting line $\lambda$ (Å)** | **Observed solar regions** | **Instruments** | **FWHM (Å)** | **References** |
| 1333.475 | 0-4 | R0 | Si IV 1393.76 | Sunspot | HRTS | 0.099 | Jordan *et al.* (1977, 1978) |
| | | | | Flare | Skylab | – | Cohen *et al.* (1978) |
| | | | | Sunspot | HRTS | – | Bartoe *et al.* (1979) |
| | | | | Umbra, quiet region, limb | HRTS + Skylab | – | Sandlin *et al.* (1986) |
| | | | | Flare | IRIS | – | Li *et al.* (2016) |
| 1333.797 | 0-4 | R1 | Si IV 1402.77 | Sunspot | HRTS | – | Jordan *et al.* (1977) |
| | | | | Sunspot | HRTS | – | Bartoe *et al.* (1979) |
| | | | | Flare | IRIS | – | Li *et al.* (2016) |
| 1393.451 | 0-4 | P10 | C II 1334.53 | Sunspot | HRTS | – | Jordan *et al.* (1977) |
| | | | | Plage, umbra | HRTS + Skylab | – | Sandlin *et al.* (1986) |
| 1393.719 | 0-5 | R0 | Si IV 1393.76 | Sunspot | HRTS | – | Jordan *et al.* (1977) |
| 1393.732 | 1-5 | P6 | C II 1335.71 | – | – | – | – |
| 1393.961 | 0-5 | R1 | Si IV 1402.77 | Sunspot | HRTS | – | Jordan *et al.* (1977) |
| 1400.612 | 0-5 | R4 | O IV 1399.77 | Umbra, quiet region, limb | HRTS + Skylab | – | Sandlin *et al.* (1986) |
| | | | | | | – | Bartoe *et al.* (1979) |
| 1402.648 | 0-5 | P3 | Si IV 1402.77 | Umbra | HRTS | – | Jordan *et al.* (1977) |
| | | | | | – | – | Bartoe *et al.* (1979) |
| 1403.381 | 2-6 | R2 | | Umbra, quiet region, limb | HRTS + Skylab | – | Sandlin *et al.* (1986) |
| 1403.982 | 0-4 | P11 | O V 1371.29 | Light-bridge | HRTS | – | Bartoe *et al.* (1979) |
| | | | | Sunspot | HRTS | – | Bartoe *et al.* (1979) |
| 1404.750 | 0-5 | R5 | O IV 1404.81 | – | – | – | Bartoe *et al.* (1979) |

- Rotational quantum no.:
(a) For $P$, $\Delta J$ = -1
(b) For $R$, $\Delta J = +1$

- Vibrational quantum no.:
(a) $v'$ = upper level
(b) $v''$ = lower level

**$H_2$ 1333.475 Å - faint**
**$H_2$ 1333.797 Å - strong**

- Columns 1-3 - **Sesam molecular spectroscopy database** - http://sesam.obspm.fr/.

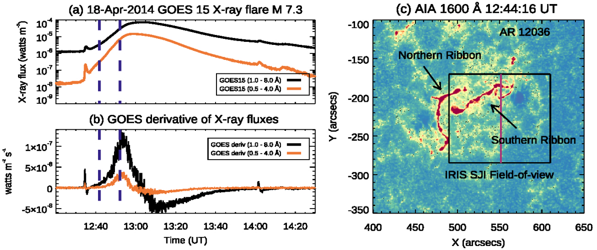
- Column 4 - adapted from the report on molecular hydrogen by Prof. Peter Young.
Link: https://pyoung.org/iris/

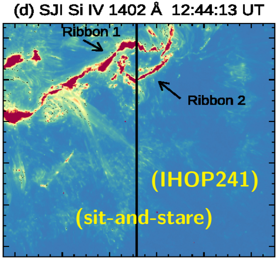
# Evidence of chromospheric molecular hydrogen emission in an IRIS flare (2021, MNRAS, 504, 2842)

- First comprehensive investigation of enhanced line emission from molecular hydrogen, **$H_2$ at 1333.79 Å**, observed at flare ribbons
- The cool $H_2$ emission is known to be **fluorescently excited by Si IV 1402.77 Å UV radiation** and provides a unique view of the temperature minimum region (TMR).
- Since Si IV is strong in flares, this should provide a good $H_2$ signal

## Research objective

- Behaviour of $H_2$ emission at flare ribbon during various phases of the flare
- The correlation between $H_2$ and Si IV emission
- Properties of cool plasma from $H_2$ spectral line
- The optical properties of plasma to the outward-going radiation, using the ratio of the two Si IV line intensities

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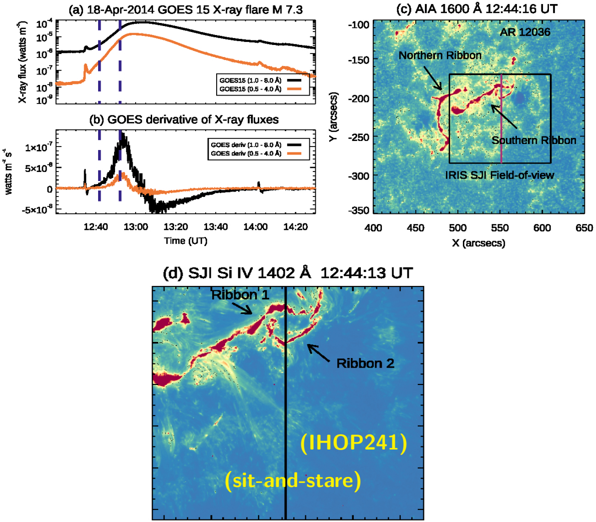
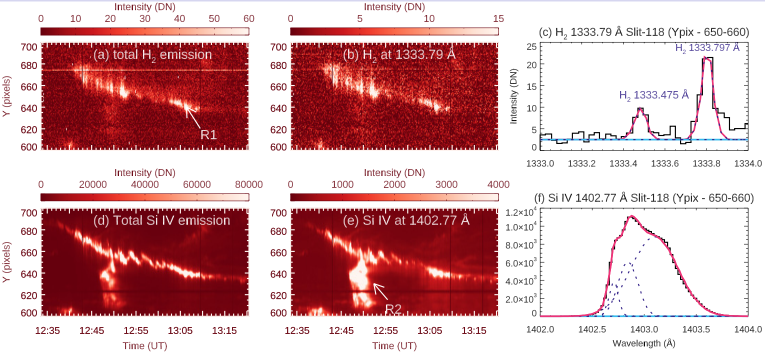
# Evidence of chromospheric molecular hydrogen emission in an IRIS flare

## SJI Si IV 1400 Å movie of M7.3 flare



# IRIS spectral images - southward movement of southern ribbon in SJI images




- **Top panel**: spectral images created by summing DNs over the wavelength ranges
  (a) $H_2$ - 1333.76 - 1333.87 Å
  (b) Si IV - 1393.5 - 1394.6 Å
- **Bottom panel**: Spectral images at single wavelength values.
  (d) $H_2$ - 1333.79 Å
  (e) Si IV - 1393.76 Å

- $H_2$ emission becomes visible when the Si IV 1402.77 Å becomes bright.
- R1 - The $H_2$ line is strongest during the flare impulsive phase, dims during the GOES peak, and brightens again during the gradual phase.
- R2 - Si IV is strong but at the same time and location $H_2$ is faint.

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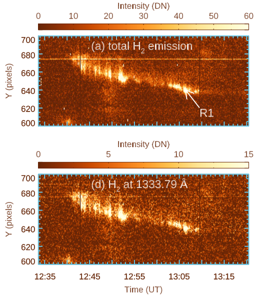
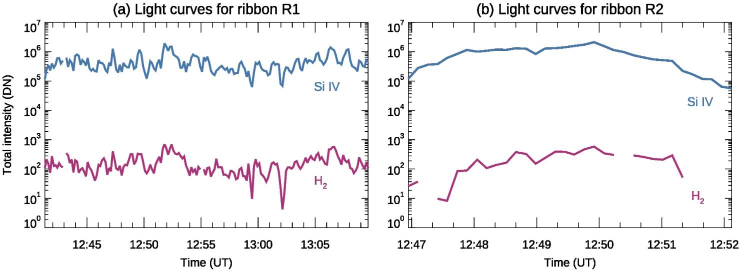
# Parameters derived from $H_2$ 1333.79 Å line observed at Ribbon 1

| Slit position Number | Y-pixel Number | Time (UT) | Centroid (Å) | FWHM (Å) | $V_{nth}$ (km $s^{-1}$) | $V_{Doppler}$ (km $s^{-1}$) |
|---|---|---|---|---|---|---|
| 54 | 672-681 | 12:41:56 | 1333.8015 | 0.056±0.013 | 10.14±3.7 | 1.21±1.5 |
| 57 | 674-678 | 12:42:24 | 1333.7981 | 0.066±0.016 | 13.06±4.0 | 0.4±1.8 |
| 63 | 667-673 | 12:43:21 | 1333.8035 | 0.065±0.012 | 12.58±3.1 | 1.7±1.3 |
| 70 | 668-672 | 12:44:27 | 1333.8121 | 0.079±0.029 | 16.19±7.2 | 3.5±3 |
| 71 | 668-673 | 12:44:36 | 1333.8073 | 0.037±0.021 | 7.19±3.4 | 2.5±1.5 |
| 75 | 666-670 | 12:45:13 | 1333.7983 | 0.065±0.018 | 12.75±4.6 | 0.5±1.9 |
| 76 | 665-669 | 12:45:23 | 1333.8072 | 0.086±0.030 | 17.67±7.5 | 2.4±3.1 |
| 77 | 664-668 | 12:45:32 | 1333.7977 | 0.042±0.015 | 6.69±3.5 | 0.35±1.6 |
| 80 | 663-668 | 12:46:01 | 1333.7905 | 0.053±0.016 | 9.16±4.6 | -1.26±1.7 |
| 85 | 661-663 | 12:46:47 | 1333.8049 | 0.065±0.018 | 12.50±4.6 | 1.9±1.8 |
| 92 | 659-663 | 12:47:53 | 1333.7911 | 0.084±0.028 | 17.45±6.8 | -1.13±2.7 |
| 93 | 659-662 | 12:48:03 | 1333.7879 | 0.063±0.018 | 12.24±4.6 | -1.84±1.9 |
| 97 | 655-660 | 12:48:40 | 1333.8018 | 0.054±0.015 | 9.80±4.2 | 1.3±1.6 |
| 98 | 655-662 | 12:48:50 | 1333.8018 | 0.078±0.020 | 16.05±4.9 | 1.3±2.03 |
| 99 | 655-662 | 12:48:59 | 1333.8044 | 0.071±0.017 | 14.07±4.3 | 1.86±1.83 |
| 100 | 656-661 | 12:49:08 | 1333.8004 | 0.044±0.016 | 7.02±4.1 | 0.96±1.6 |
| 109 | 654-659 | 12:50:33 | 1333.8179 | 0.071±0.029 | 14.1±7.4 | 4.9±2.9 |
| 111 | 654-657 | 12:50:52 | 1333.7956 | 0.044±0.017 | 7.2±4.1 | -0.11±1.92 |
| 113 | 653-660 | 12:51:10 | 1333.8109 | 0.054±0.020 | 9.17±6.0 | 3.3±2.1 |
| 114 | 654-663 | 12:51:20 | 1333.7995 | 0.059±0.018 | 11.12±4.9 | 0.76±2.0 |
| 115 | 654-659 | 12:51:29 | 1333.8036 | 0.060±0.020 | 11.36±5.3 | 1.6±2.03 |
| 116 | 650-660 | 12:51:39 | 1333.7965 | 0.060±0.014 | 11.49±3.8 | 0.08±1.6 |
| 117 | 650-661 | 12:51:48 | 1333.7978 | 0.075±0.015 | 15.34±3.7 | 0.4±1.6 |
| 118 | 650-660 | 12:51:57 | 1333.8037 | 0.065±0.012 | 12.84±3.1 | 1.7±1.3 |




- The $H_2$ 1333.79 Å line is broad.
- Non-thermal speeds = 7-18 km/s.
- Measured $H_2$ Doppler shifts are consistent with zero within the errors, indicating negligible bulk flows along the line-of-sight.

# Correlations between the exciter wavelength and the fluorescent emission




## Results

- For R1 - the overall pattern of $H_2$ intensity variation is very similar to the intensity variation in Si IV
- shows many of the same small-scale features
- For R2, there is little small-scale intensity variation in Si IV and $H_2$.

## $H_2$ emission

- Ribbon 1 - The $H_2$ emission becomes visible when the Si IV 1402.77 Å becomes bright.
- supporting the notion that fluorescent excitation is responsible.
- Ribbon 2 is very bright at Si IV 1402.77 Å, but the $H_2$ at the same time and location is faint.

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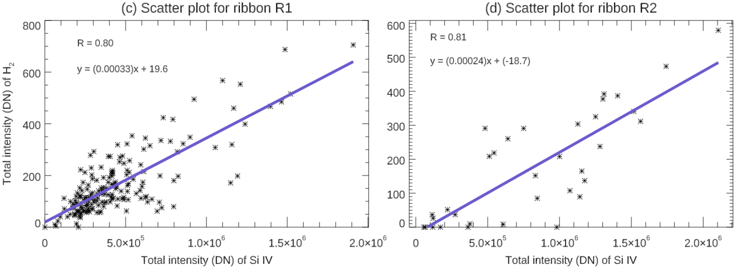
# Correlations between the exciter wavelength and the fluorescent emission




## Results

- A strong a positive correlation between $H_2$ and Si IV line intensities
- Correlation coefficient for both ribbons - same order of magnitude, but the gradient differs by 50%
- Shallower gradient for the Ribbon 2.

## $H_2$ emission at Ribbon 2

- Ribbon 2 is very bright at Si IV 1402.77 Å, but the $H_2$ at the same time and location is faint.
- It may be that the opacity of the chromosphere down to this level at the R2 location is higher than at the R1 location.
- Ribbon 1 crosses a plage region, whereas; Ribbon 2 crosses a spot penumbra, which would be expected to have different temperature, density and hence, opacity structures.

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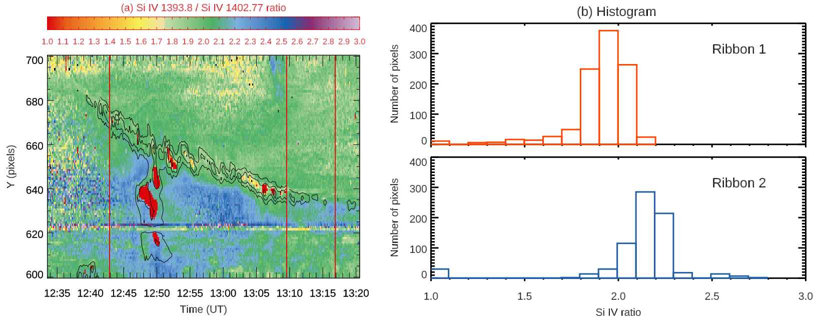
# Optical properties of plasma - the ratio of the two Si IV line intensities




## Flare simulations

- A ratio of 2 normally indicates an optically thin plasma.
- However, detailed flare radiation hydrodynamics simulations by Kerr *et al.* (2019) demonstrate that **opacity effects can lead to a range of ratios from 1.8 to 2.3.**

## Si IV ratio results

- At R1, ratio = 2 (during the impulsive phase) - indicates an optically thin plasma.
- At R1, ratio = 1.8 – 2.0 (at GOES flare peak) - indicates an increase in the opacity effects (Mathioudakis *et al.* 1999)
- At R2, where ratio > 2.0 - a contribution from resonant scattering (Gontikakis & Vial 2018)

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## Summary - Mulay S. M., Fletcher L., 2021, MNRAS, 504, 2842

- **$H_2$ emission was observed in flare ribbons** - GOES M7.3 X-ray flare
    - $H_2$ line is **strongest during the flare impulsive phase**, dims during the GOES peak, and brightens again during the gradual decay phase.

- **The $H_2$ line is broadened,**
    - corresponding to **non-thermal speeds in the range 7-18 km/s.**

- **$H_2$ Doppler shifts are consistent with zero within the errors**, indicating negligible bulk flows along the line-of-sight.

- From **the ratio of Si IV (1393.76/1402.77)**, we deduce that
    - the plasma is **optically thin to Si IV (where the ratio = 2) during the impulsive phase of the flare** in locations where strong $H_2$ emission was observed.
    - In contrast, the ratio differs from optically thin value of 2 in parts of ribbons, indicating a role for opacity effects.

## Conclusions

- **A strong spatial and temporal correlation between $H_2$ and Si IV emission was evident supporting the notion that fluorescent excitation is responsible.**

- $H_2$ emission gave a new view of conditions in the temperature minimum region (TMR) during flare.

- Our study is useful for constraining further models of the chromosphere and TMR during flares.

## Future research plans

- IRIS $H_2$ emission in various C, M and X-class flares and relationship with Si IV emission.

- **Jaeggli *et al.* 2018** - UV opacity is dominated by the photoionisation of neutral C and S.

- Investigation of IRIS C I 1354.29 Å and S I 1401.51 Å and relation with $H_2$.

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# References and Acknowledgements

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