Evidence of chromospheric molecular hydrogen emission in an IRIS flare

Dr. Sargam Mulay[1], Prof. Lyndsay Fletcher[1,2]

[1]School of Physics and Astronomy, University of Glasgow, UK

[2]Rosseland Centre for Solar Physics, University of Oslo, P.O.Box 1029 Blindern, NO-0315 Oslo, Norway

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

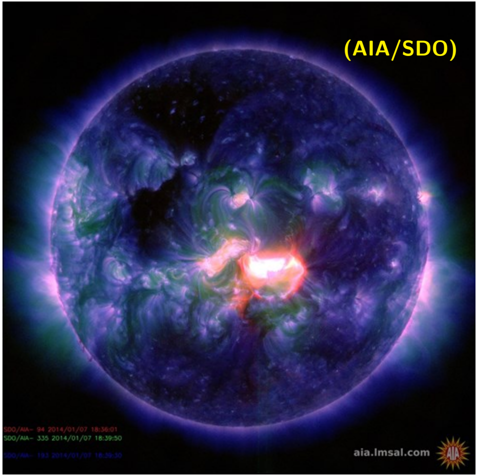
Overview

- Introduction to solar flares
- Formation of molecular hydrogen H_2 emission
- H_2 observed in different solar events
- Chromospheric H_2 emission observed in an IRIS flare
- Summary
- Future research plan

Introduction to solar flares

Solar flares

- sudden bursts that produce bright emissions in different layers of the solar atmosphere
- **Magnetic reconnection** - plays the main role in restructuring the magnetic field and converting magnetic energy into heat and kinetic energy of particle beams
- **Plasma heating** - 10 MK in Corona and it is evident from emission observed in high temperature extreme ultraviolet spectral lines
- **Particle acceleration** - towards the lower layer where they collisionally heat the dense chromosphere.
- **Radiation** - results in generation of Hard X-ray and ultraviolet emission.
- **Measurement of plasma parameters** - electron number density, nonthermal velocities, Doppler shift, spectral profiles from spectroscopic observations are important to understand the dynamic nature of chromosphere, transition region and corona.



Dr. Sargam Mulay (email: Sargam.Mulay@glasgow.ac.uk) University of Glasgow, UK (ORCID iD: 0000-0002-9242-2643)

Recent study of solar flares using the Interface Region Imaging Spectrograph (IRIS)

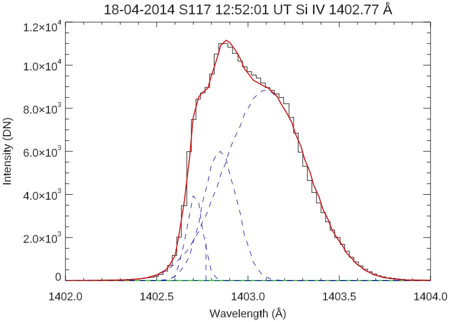
Jeffrey *et al.* (2018)

- studied a small X-ray flare - B class
- IRIS spectra - a very high cadence of 1.7 sec

- **Observations**
- Si IV 1402.77 Å - intensity and nonthermal line broadening
- observed that the increase and peak of the nonthermal line width of the Si IV line preceded the rise and peak of line intensity

- **Results**
- MHD turbulence was present in flare footpoints before the plasma was heated
- the turbulence may have contributed towards the heating

(Mulay *et al.* 2021)



Selection of IRIS solar flare observations -
- GOES X-ray class - C and M class flares were selected to avoid saturation of spectral lines
- IRIS slit step cadence - 1-10 sec - to study the rapid evolution of a flare and their spectral signatures
- IRIS slit should have observed Si IV 1393.8 and 1402.77 Å emission from flare ribbons - in order to study whether the plasma is optically thin or thick.

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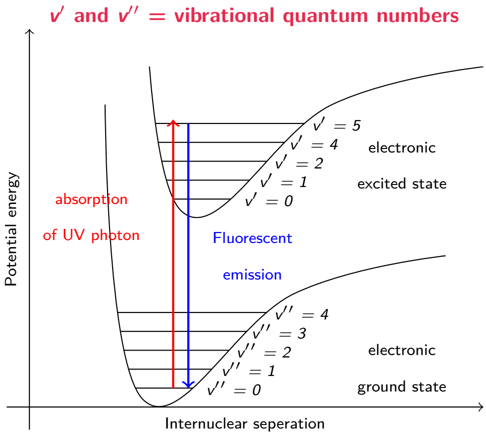
Emission from molecular hydrogen H_2



A schematic representation of the ground and first excited electronic states of the hydrogen molecule, H_2.

- H_2 is a homonuclear molecule - no intrinsic dipole moment.

- Every electronic state has multiple vibrational and rotational states of different energies.

- Excitation or de-excitation between electronic states can be between any of these vibrational or rotational states allowed by quantum-mechanical selection rules.

- The electronic excitation from the ground state to the first (Lyman band) or second (Werner band) electronic excited state of H_2 molecule occur due to absorption of far-UV photons.

- The de-excitation to the electronic ground state (with a time scale of 10^{-8} sec) occurs by emitting the far-UV emission lines (fluorescence) in Lyman or Werner bands of H_2.

Emission from molecular hydrogen H_2 in solar atmosphere

H_2 emission

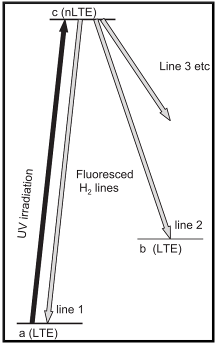
- Formation temperature = 4200 K (Innes 2008)
- Provides information about the Temperature Minimum Region (TMR)
- Formed by **photo-excitation (fluorescence) by ultraviolet (UV) radiation** from the transition region.

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

Exciting line λ (Å)	Fluorescent channel (ν' - ν'')	Transition (ν' - ν'')	Branch ($\Delta J = \pm 1$)	H_2 λ (Å)	Wavenumber (cm^{-1})
Si IV 1393.76	0-5 R0, 1393.719	0-4	R0	1333.475	74992.02
		0-5	R0	1393.719	71750.48
		0-4	P2	1338.565	74706.86
		0-5	P2	1398.954	71481.99
Si IV 1402.77	0-5 P3,1402.648	0-4	R1	1333.797	74973.93
		0-4	P3	1342.257	74501.39
		0-5	R1	1393.961	71738.02
C II 1334.53	0-3 P10, 1334.501	0-4	P10	1393.451	71764.30
C II 1335.71	1-4 P6, 1335.581	1-5	P6	1393.732	71749.83

- **Rotational quantum number**
(a) For *P*, ΔJ = -1
(b) For *R*, ΔJ = +1

- **Vibrational quantum number**
(a) ν' = upper level
(b) ν'' = lower level

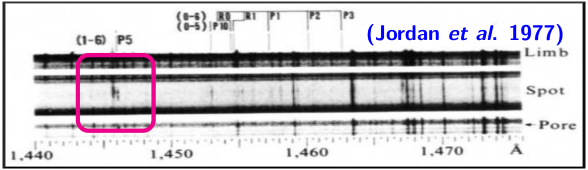
- Column 6 - energy levels from Abgrall *et al.* (1993)

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

- The absorption of far-UV photons gives rise to electronic excitation in H_2.
- There are a number of vibrational levels in each electronic state, so de-excitation to the ground electronic state leads to the formation of H_2 lines at a range of wavelengths.
- Excitation of the upper state requires photons of specific wavelength, resulting from emission in far-UV atomic lines, or continuum, or indeed other H_2 molecular lines.

Solar observations of molecular hydrogen H_2 emission

- **First solar molecular H_2 observation - HRTS**
- **Jordan *et al.* (1977, 1978)** - sunspot umbra
- Lyman band of H_2 (P and R branches)
- fluoresced by H Lyman α red wing photons, and by strong transition region lines, C II, Si IV & O IV



- **Cohen *et al.* (1978)** - Skylab - solar flare

- at the beginning of the flare gradual phase, and the spectrograph slit reportedly did not cross the flare ribbon.

- **Bartoe *et al.* (1979)** - HRTS - Sunspot

- First HRTS flight Sunspot umbra - fluoresced by the O VI resonance line
- Werner band (H_2 lines in Q branch that corresponds to $\Delta J = 0$)
- H_2 lines decreased rapidly in intensity with time, presumably as the line intensity and width of the exciting transition region line decreased.

- **Sandlin *et al.* (1986)** - Quiet sun

- Atlas of H_2 lines

- **Schüehle *et al.* (1999)** - SUMER - Sunspot

- **Innes (2008)** - SUMER

- active region plage, the footpoints of X-ray microflares,
- near the footpoint of a brightening X-ray loop and at the location of strong transition region outflows

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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 λ (Å)	**Transition (v' - v'')**	**Branch ($\Delta J = \pm 1$)**	**Exciting line λ (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, ΔJ = -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/

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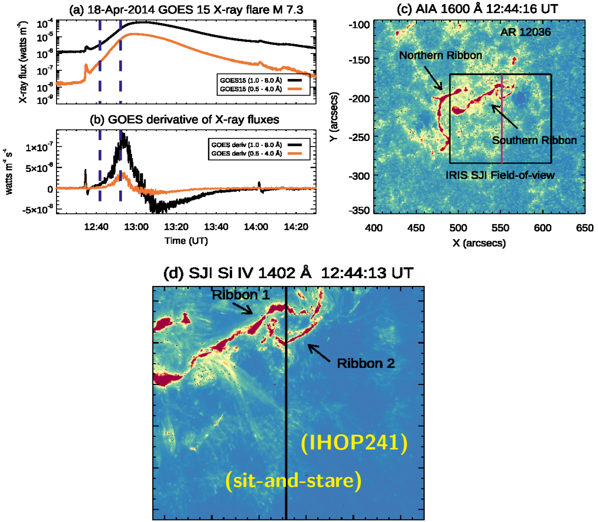
Evidence of chromospheric molecular hydrogen emission in an IRIS flare (2021, MNRAS, 504, 2842)

- 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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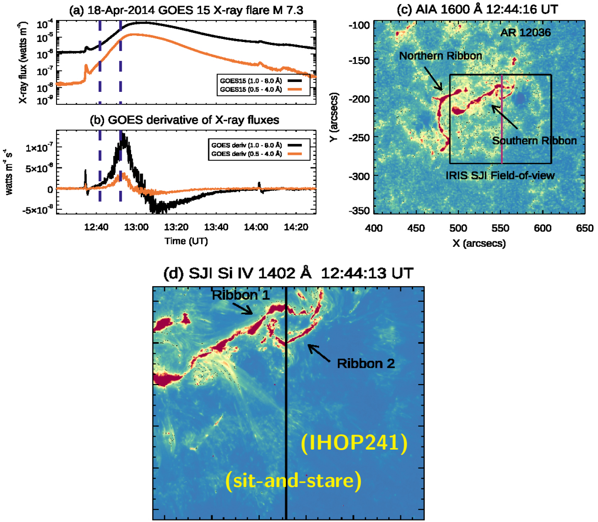
Evidence of chromospheric molecular hydrogen emission in an IRIS flare

SJI Si IV 1400 Å movie of M7.3 flare



This slide contains a movie of M7.3 flare. Kindly open this pdf in Okular to watch the movie.

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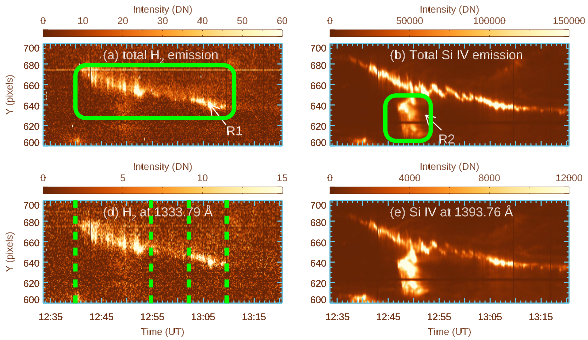
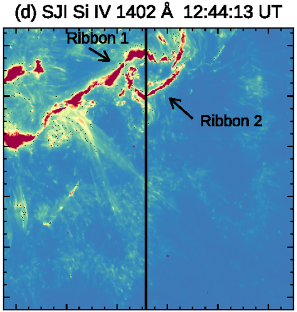
IRIS spectral images - southward movement of southern ribbon in SJI images





- **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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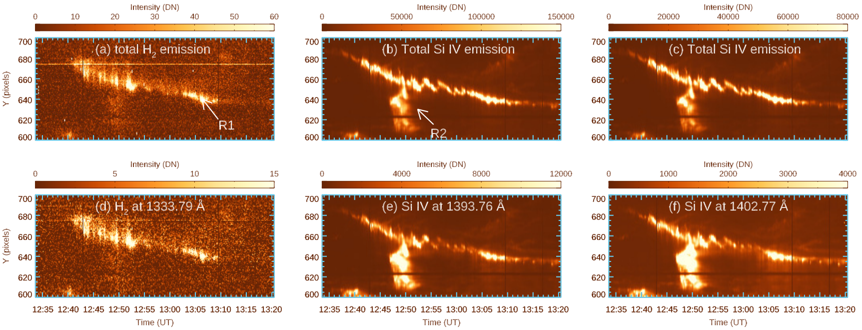

- **Top panel**: spectral images created by summing DNs over the wavelength ranges
  (a) H_2 - 1333.76 - 1333.87 Å
  (b) Si IV - 1393.5 - 1394.6 Å
  (c) Si IV - 1402.5 - 1403.6 Å

- **Bottom panel**: Spectral images at single wavelength values.
  (d) H_2 - 1333.79 Å
  (e) Si IV - 1393.76 Å
  (f) Si IV - 1402.77 Å

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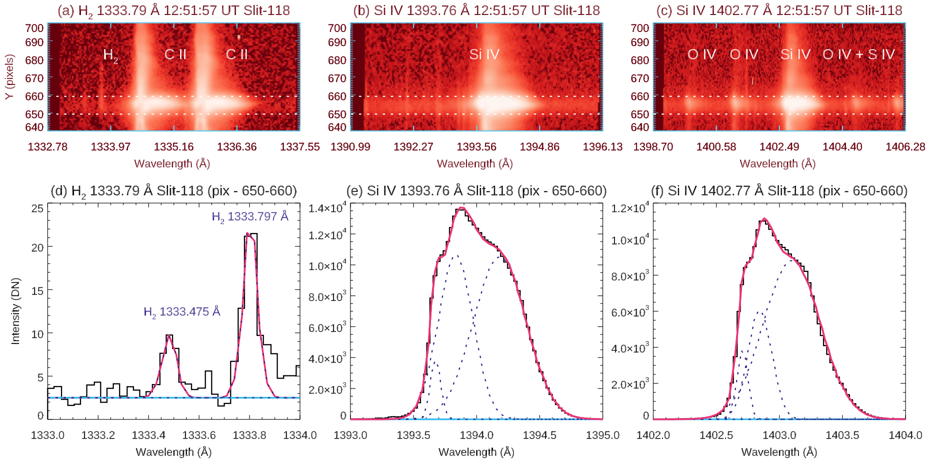
Spectral analysis - detector images and line profiles



- The averaged spectra were obtained by averaging pixels between 650 and 660 along the slit.The white dashed lines indicate emission in these pixels.

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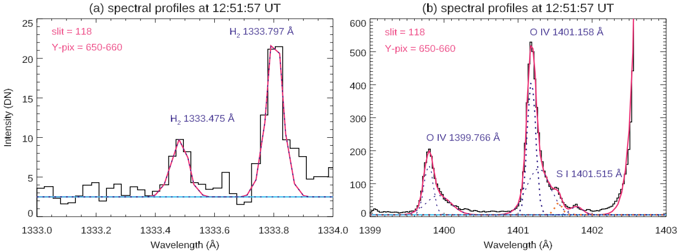
Understanding a possible blend of S I (1333.80 Å) with the H_2 (1333.797 Å)



- Reference line - S I 1401.51 Å

- We studied the behaviour of S I 1401.51 Å line (in intensity, velocity, and width) and compared that with H_2 1333.797 Å line.

Data analysis

- Total spectral profiles - 24
- Only 11 spectral profiles were selected and fitted with a single Gaussian.
- We derived the intensities, Doppler velocities and widths of the line and compared with H_2 parameters.
- The remaining spectra were slightly narrow in the core and broader in the wings, and two Gaussian components were needed to fit the line. Hence, we did not use these line profiles for further analysis.

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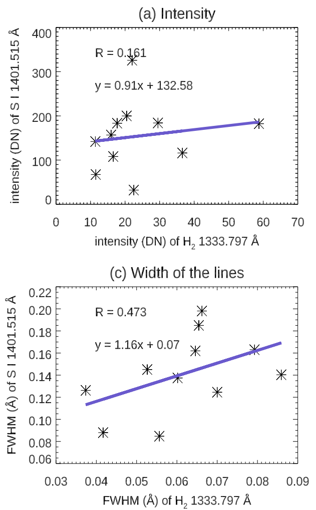

Results

- The Pearson correlation coefficients:

1) Intensity - weak positive correlation
2) Doppler Velocity - weak negative correlation
3) Width - moderate correlation

Conclusion

- The above results confirmed that **the behaviour of the S I 1401.51 Å line is different than H_2 line.**

- Hence, we conclude that **there is an absence of any significant S I line contribution in H_2 line at 1333.79 Å.**

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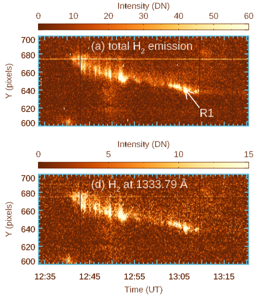
Parameters derived from H_2 1333.79 Å line observed at Ribbon 1

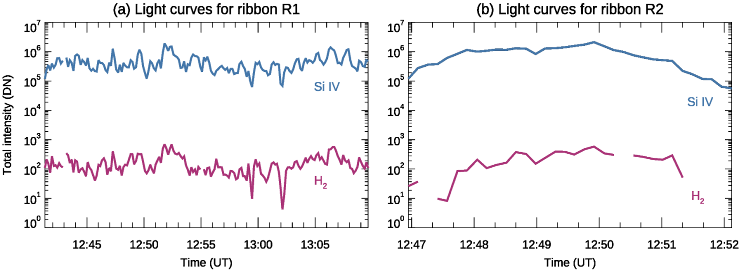
Slit position Number	Y-pixel Number	Time (UT)	Centroid (Å)	FWHM (Å)	V_{nth} (km s^{-1})	$V_{Doppler}$ (km s^{-1})
54	672-681	12:41:56	1333.8015	0.056±0.013	10.14±3.7	1.21±1.5
57	674-678	12:42:24	1333.7981	0.066±0.016	13.06±4.0	0.4±1.8
63	667-673	12:43:21	1333.8035	0.065±0.012	12.58±3.1	1.7±1.3
70	668-672	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.

Dr. Sargam Mulay (email: Sargam.Mulay@glasgow.ac.uk) University of Glasgow, UK (ORCID iD: 0000-0002-9242-2643)

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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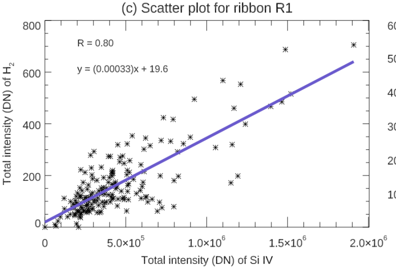

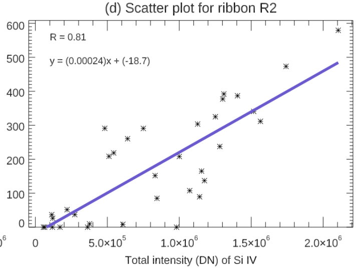

Results

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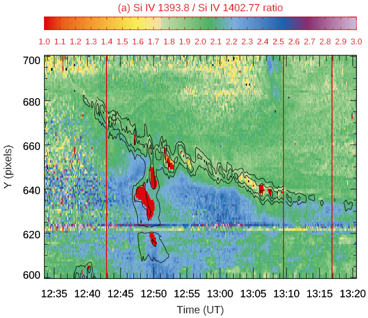
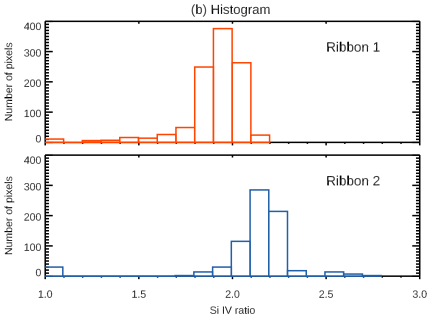
Optical properties of plasma - the ratio of the two Si IV line intensities





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)

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.

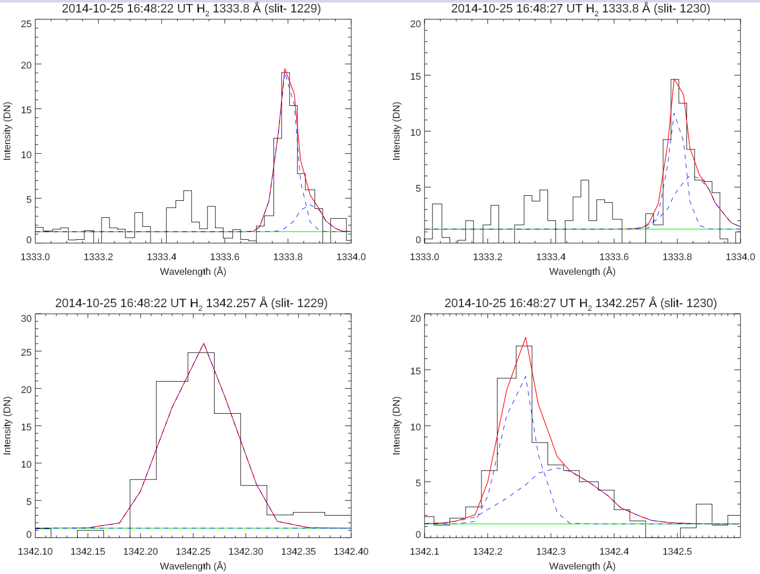
Conclusions

- **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.

Current research - Preliminary analysis of H_2 lines during GOES X1.0 flare



- **Some unresolved questions**

1) Why does the behaviour of H_2 line change rapidly (with time scale of 5 sec)?

2) Why don't we see the H_2 line at 1333.47 Å even though other H_2 lines are present?

3) Why do we see stationary and moving components in one H_2 line but not in other?
- even though the same Si IV line at 1402.77 Å is responsible for both lines

Dr. Sargam Mulay (email: Sargam.Mulay@glasgow.ac.uk) University of Glasgow, UK (ORCID iD: 0000-0002-9242-2643)

References and Acknowledgements

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Acknowledgements

- We acknowledge support from the UK Research and Innovationâs Science and Technology Facilities Council (STFC) under grant award numbers ST/P000533/1 and ST/T000422/1.

- We would like to thank Dr. Peter Young (NASA), Dr. Giulio Del Zanna, and Dr. Helen Mason (University of Cambridge, UK) for the discussion and valuable comments.

- IRIS is a NASA small explorer mission developed and operated by LMSAL with mission operations executed at NASA Ames Research center and major contributions to downlink communications funded by ESA and the Norwegian Space Centre.

Dr. Sargam Mulay (email: Sargam.Mulay@glasgow.ac.uk) University of Glasgow, UK (ORCID iD: 0000-0002-9242-2643)