A detailed investigation of molecular hydrogen at three flare ribbons

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Overview

- Formation of cool molecular hydrogen H_2 emission
- H_2 emission observed in three IRIS flares
- Summary
- Future research plans

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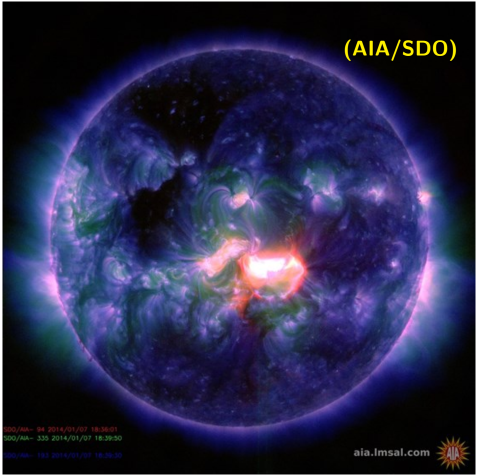
Introduction to solar flares

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 layers 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.



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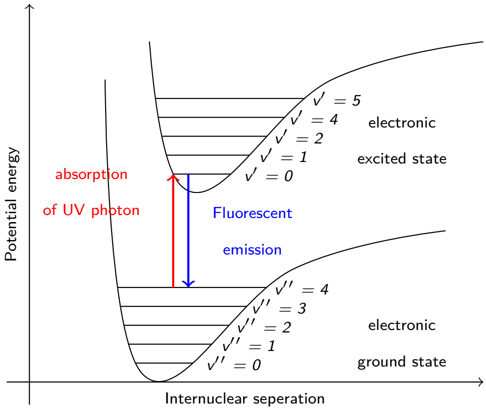
Emission from molecular hydrogen H_2

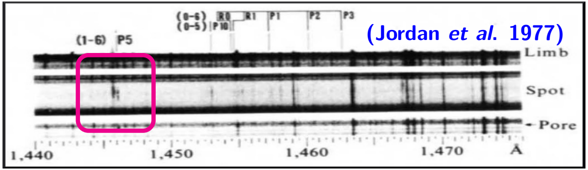


A schematic representation of the ground and first excited electronic states of the hydrogen molecule, H_2.

- H_2 is a homonuclear molecule - no intrinsic dipole moment.
- Every electronic state has multiple vibrational and rotational (sub-)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.

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



(Jordan *et al.* 1977)

- **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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Emission from molecular hydrogen H_2 in solar atmosphere

H_2 emission

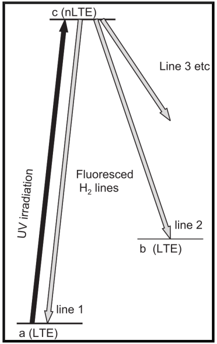
- Formation temperature = 4200 K (Innes 2008)
- Provides information about the Temperature Minimum Region (TMR)
- Formed by **photo-excitation (fluorescence) by ultraviolet (UV) radiation** from the transition region.

Question?

- Can bright UV line radiation that excites H_2 fluorescence penetrates 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 determine 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 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, ΔJ = +1
- Vibrational quantum no.:
  (a) v' = upper level
  (b) v'' = lower level
- 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/

(Mulay and Fletcher 2021)

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Exciting line λ (Å)	Fluorescent channel (v' - v'')	Transition (v' - v'')	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 transition, $\Delta J = v'$ - v'' = -1
  (b) For R transition, $\Delta J = v'$ - v'' = +1
- **Vibrational quantum number**
  (a) v' = upper level
  (b) v'' = 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.

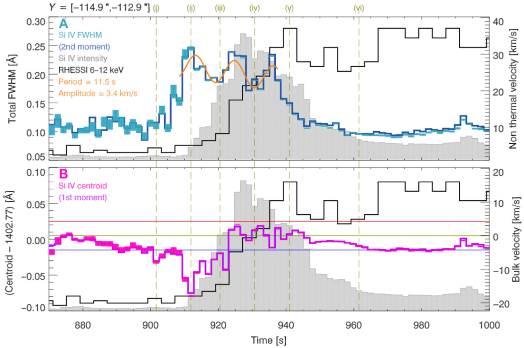
Motivation

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



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
- 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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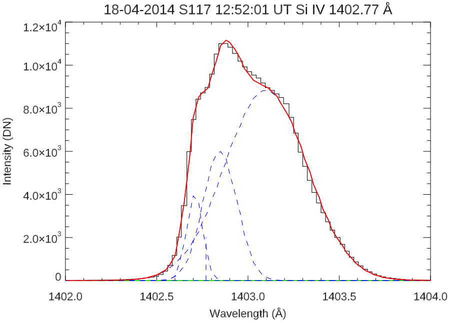
(Mulay *et al.* 2021)



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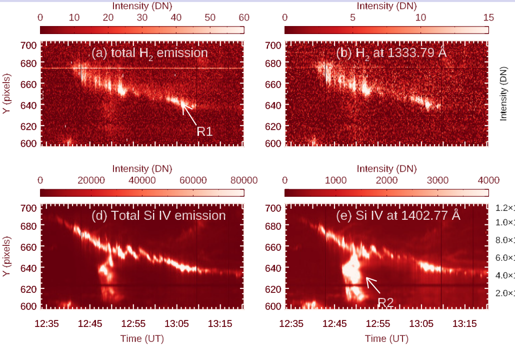
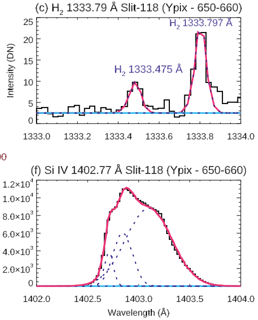
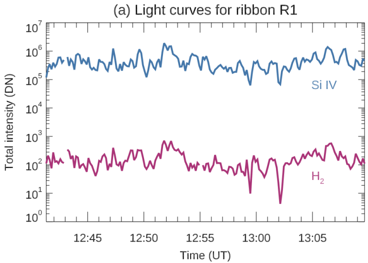
Evidence of chromospheric molecular hydrogen emission in an IRIS flare (Mulay and Fletcher 2021, MNRAS)





Strong spatial and temporal correlation between H_2 and Si IV



- **GOES M7.3 flare** - 18-Apr-2014 - 12:30-13:20 UT - IRIS 10 sec cadence

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

- **Left panel**: spectral images created by summing DNs over the wavelength ranges
(a) H_2 - 1333.76 - 1333.87 Å
(d) Si IV - 1402.5 - 1403.6 Å
- **Middle panel**: Spectral images at single wavelength values.
(b) H_2 - 1333.79 Å
(e) Si IV - 1402.77 Å

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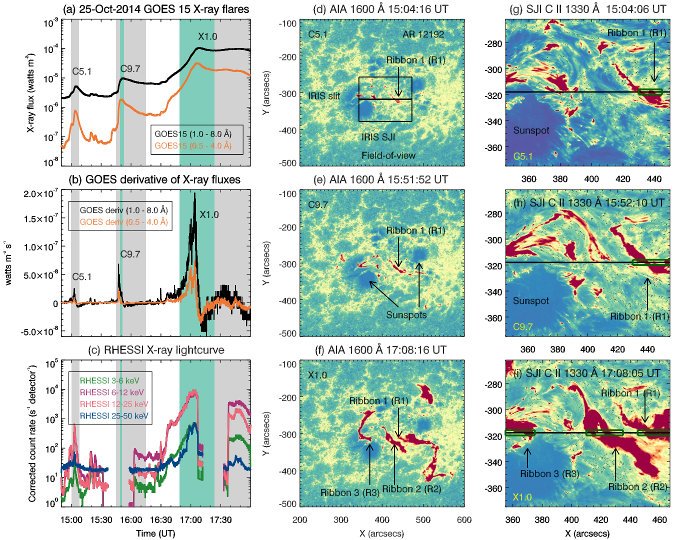
A detailed investigation of molecular hydrogen at three flare ribbons



- GOES X-ray flares - C5.1, C9.7 and X1.0

- **Objective**

  Identifying the sources of the nonthermal profiles/velocities (and turbulence) at the flare ribbon locations

- **The study involves**

  1) High cadence data - 5 seconds - sit-and-stare
  2) A full IRIS spectra for three flares originate at the same location
  3) the behaviour of different H_2 lines during different phases of flares
  4) A diagnostic of non-thermal velocities in the lower chromosphere - C I, O I, S I, and Cl I lines

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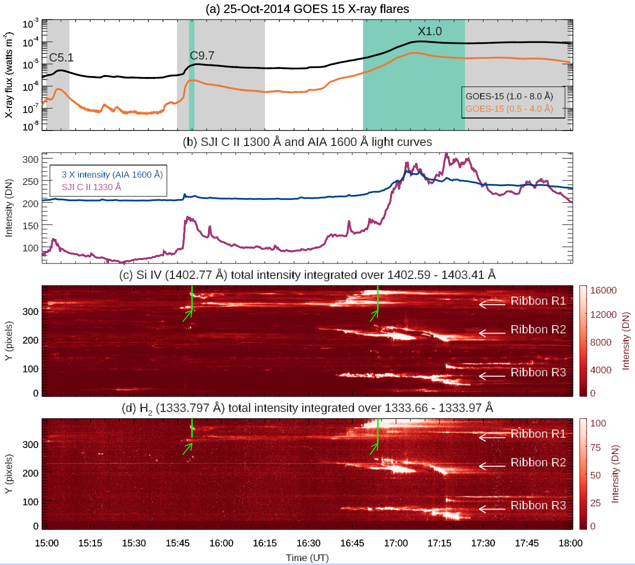
Spectral images and temporal evolution of X-rays, and UV lines

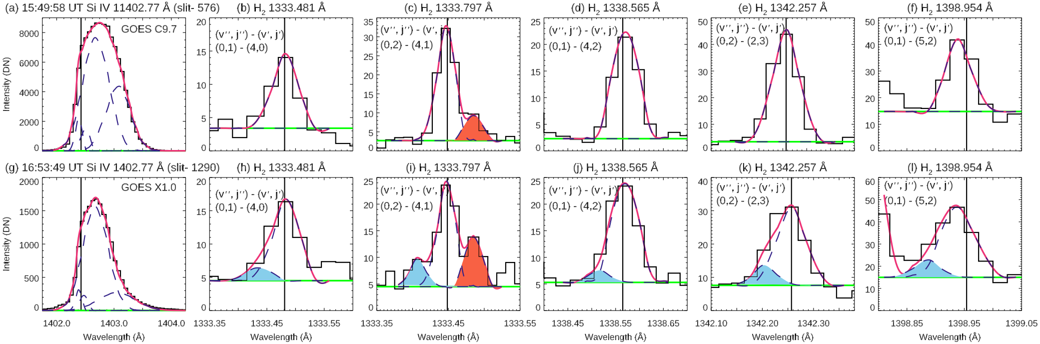


- **Panel a and b:** Temporal evolution of flare emission at
(i) GOES X-ray channels
(ii) AIA 1600 Å
(iii) SJI C II 1330 Å

- **Panel c and d:** IRIS spectral images created by summing DNs over the wavelength ranges
(b) H_2 - 1333.66-1333.97 Å
(c) Si IV - 1402.59-1403.41 Å

- Green lines with arrows indicate the timings during the flares where we obtained the H_2 and Si IV spectra

H_2 and Si IV spectra at ribbon 1 during C9.7 and X1.0 flares



Exciting line λ (Å)	Transition (v' - v'')	Transition (j' - j'')	Branch ($\Delta J = \pm 1$)	H_2 λ (Å)
Si IV 1393.76	0-4	1-0	R0	1333.481
	0-4	1-2	P2	1338.565
	0-5	1-2	P2	1398.954
Si IV 1402.77	0-4	2-1	R1	1333.797
	0-4	2-3	P3	1342.257

- **Rotational quantum number**
  (a) j' = upper level
  (b) j'' = lower level
- **Vibrational quantum number**
  (a) v' = upper level
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  (c) For P transition, $\Delta J = v' - v''$ = -1
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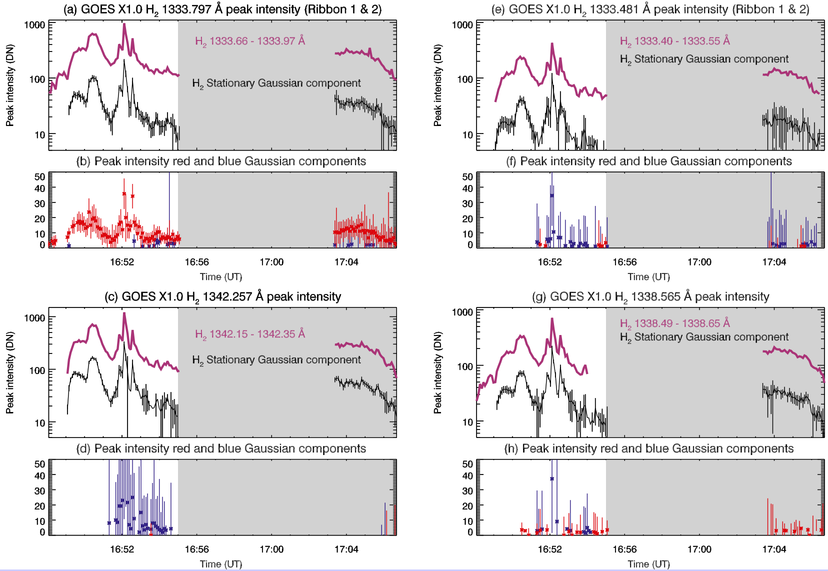
Comparison of intensities of H_2 lines during X1.0 flares - Ribbon 1 & 2



- Violet curves - total H_2 intensities summed over wavelength ranges
- Black curves - stationary component of H_2 (after fitting the Gaussian).
- Red and blue curves - red and blue wing components of H_2 (after fitting the Gaussian).
- The intensity variation in the stationary components in four H_2 lines are very similar but only differ in having blue and red-wing Gaussian components.

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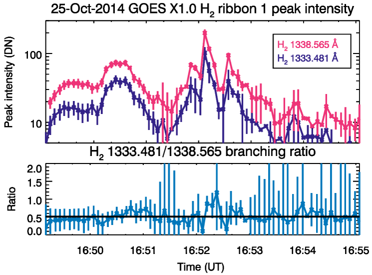
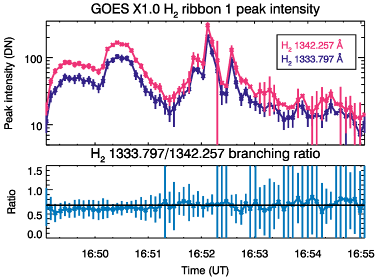
Exciting line λ (Å)	Upper level (v' - j')	Lower level (v'' - j'')	Branch ($\Delta J = \pm 1$)	H_2 λ (Å)	Transition probability	Oscillator Strength	Branching ratio
Si IV 1393.76	0-1	4-0	R0	1333.475	1.56316e+08	0.1251	0.08292*
	0-1	4-2	P2	1338.565	3.08291e+08	0.04971	0.1635
Si IV 1402.77	0-2	4-1	R1	1333.797	1.87859e+08	0.08355	0.1011*
	0-2	2-3	P3	1342.257	2.75700e+08	0.05322	0.1483

* Jaeggli et al. 2014, AAS Meeting 224 #323.06





- The transitions with higher probability will produce more photons than the transitions with lower probability.
- The branching ratio is a way of expressing this probability, it's the probability that one transition occurs divided by the total probability from all the downward transitions from that upper level.
- In the optically thin case, the line intensities will follow the branching ratios exactly, i.e. all the lines belonging to a particular upper level will have intensities that are related by their branching ratio.

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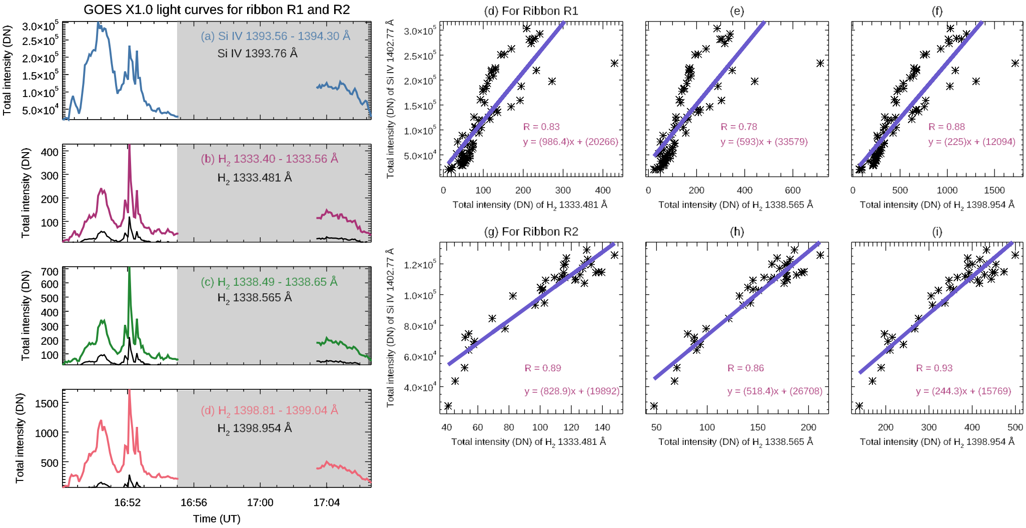
Correlation between H_2 and Si IV emission at ribbon 1 & 2 during X1.0 flares



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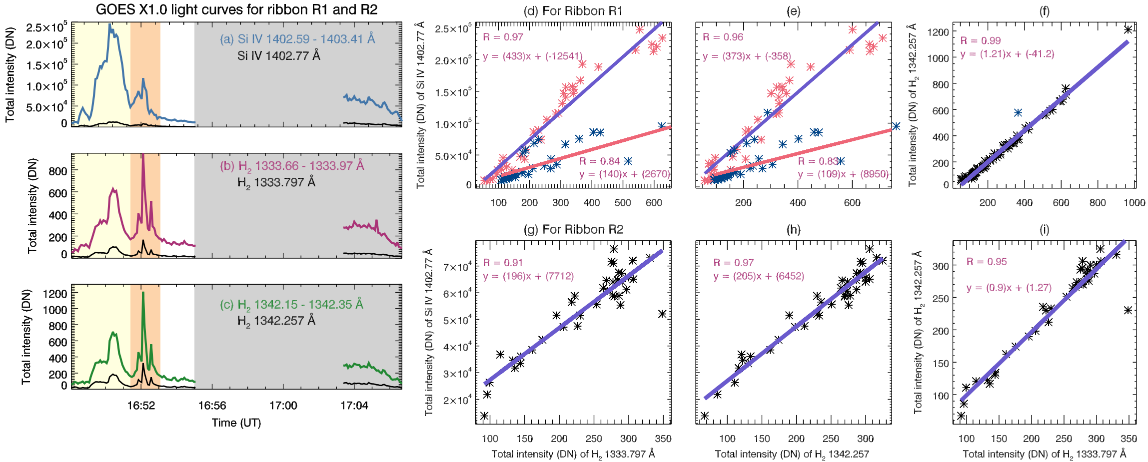

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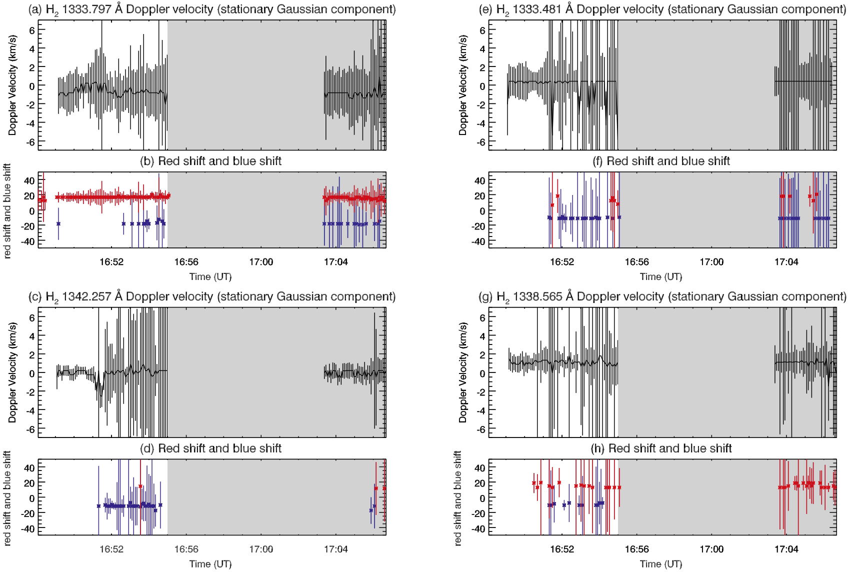
Comparison of Doppler velocities of H_2 lines during X1.0 flares - Ribbon 1 & 2



- The black curves indicate Doppler velocities for the stationary component of H_2. The red and blue curves indicate their red and blue-shifted components respectively.
- Small Doppler shifts were observed. Mostly they were consistent with zero within the errors - indicating **negligible bulk flows along the line of sight.**

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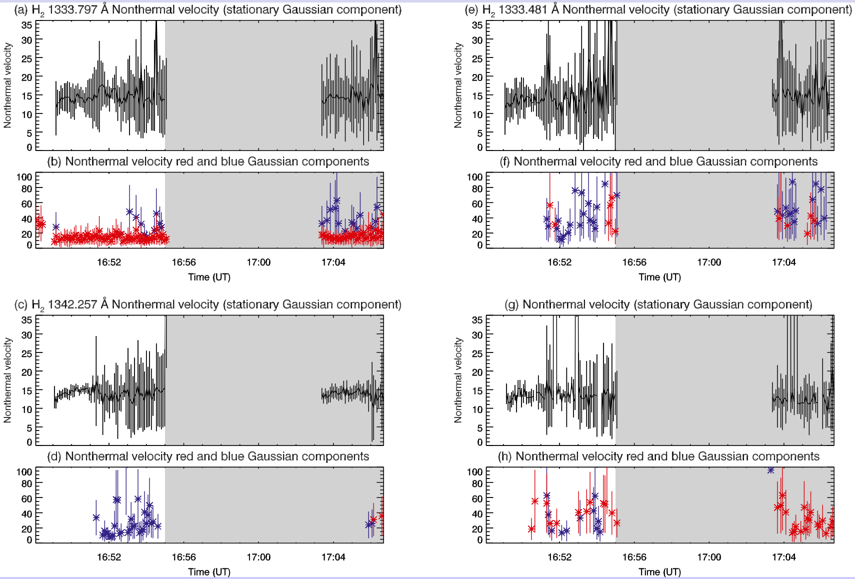
Comparison of nonthermal velocities of H_2 lines during X1.0 flares - Ribbon 1 & 2



- The black curves indicate Nonthermal velocities for the stationary component of H_2 and blue and red curves are the Nonthermal velocities for blue and red wing Gaussian components.
- The nonthermal velocities are ranging from **~10–20 km/s.**

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Summary - Mulay S. M., Fletcher L., Hudson H., Labrosse, N. in preparation

- **H_2 emission was observed in flare ribbons** - GOES C5.1, C9.7, and X1.0 X-ray flare
  - H_2 emission was observed in the impulsive rise phase of the C9.7 flare whereas strong H_2 emission was observed before the X1.0 flare started and H_2 emission continued in the impulsive phase

- **Spatial and temporal correlation between H_2 and Si IV emission observed in flare ribbons**
  - A strong positive correlation was observed between H_2 and Si IV emission.
  - A strong positive correlation was observed between two H_2 lines which are fluoresced by the same Si IV emission.

- **The H_2 lines are broadened,**
  - corresponding to **non-thermal speeds in the range 10-20 km/s.**

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

- From **Branching ratio of H_2 lines**
  - The intensity of two H_2 lines (originated from the same upper-level) follow the branching ratio.
  - This indicates that H_2 emission is formed under the optically thin plasma conditions.

Future plans

- **Some unresolved questions**
- Why does the behaviour of H_2 lines change rapidly (with a time scale of 5 sec)?
- Why do we see stationary and moving components in one H_2 line but not in other H_2 line? - even though the same Si IV line at 1402.77 Å is responsible for the emission of both H_2 lines

- **Future research**
- Understanding the changes in Si IV line profiles and their effects on H_2 lines using RADYN simulations
- A diagnostic of non-thermal velocities in the lower chromosphere - C I, O I, and Cl I lines and comparison with H_2 lines

References and Acknowledgements

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