

Investigating Molecular Hydrogen in Active Regions with IRIS

Sarah A. Jaeggli¹, Philip G. Judge², Steven H. Saar³,
Adrian N. Daw⁴, & The IRIS Team

¹Montana State University

²High Altitude Observatory

³Harvard-Smithsonian Center for Astrophysics

⁴Goddard Space Flight Center



Introduction

Molecular hydrogen (H_2) should be the most abundant molecular species in sunspots and if it contributes significantly to the gas pressure it may have interesting consequences for sunspot formation and evolution (Jaeggli, Lin, & Uitenbroek, 2012). A direct measurement of the H_2 emission or absorption in a sunspot could provide the information necessary to derive the molecular fraction. However, recent observations of the fluorescent H_2 lines in the FUV taken with the Interface Region Imaging Spectrograph (IRIS) show that its signature seems to be absent from above the sunspot umbra, and instead appears most brightly during flares. The first reports of these lines in observations from HRTS identified them in active region features such as light bridges and in sunspots, in addition to flaring regions (Jordan et al., 1977; Jordan et al., 1978; Bartoe et al., 1979). Now, with IRIS's superior spatial resolution, cadence, and context imaging (see De Pontieu et al., 2014), we are beginning to identify the mechanisms involved in H_2 fluorescence.

The H_2 lines in the IRIS range are produced when bright lines similar in wavelength to H_2 transitions excite an upper energy level in the molecular Lyman band. The downward transitions occur with differing probabilities, producing a fluorescence spectrum. The intensity of H_2 fluorescence should

be highly correlated with the properties of the exciting line, depending on its intensity, velocity, and width. The lines responsible for H₂ fluorescence in the IRIS ranges are C II 1334.53 and 1335.70 Å, Si IV 1393.76 and 1402.77 Å, and Lyman α 1215.67 Å, but they may also be excited by bright continuum in flares.

It is difficult for UV photons to travel very far into the lower atmosphere due to the high opacity from photoionization of Si I and C I which are optically thick in the low chromosphere. The H₂ emission can originate no lower than the low chromosphere. Because H₂ is formed in a 3-body process, and is therefore highly pressure sensitive, there are probably relatively few H₂ molecules present.

In this poster we analyze IRIS FUV observations of H₂ in active regions during one M-class and one X-class flare, examining the correlation between the intensity of the H₂ lines and the lines which are responsible for their excitation. We particularly focus on differentiating places where H₂ is abundant, e.g. holes in the chromospheric opacity where FUV photons can enter more deeply into the solar atmosphere, and places where the FUV radiation field is intense.

Find the movies online at:

<http://solar.physics.montana.edu/jaeggli/wip/iris/movies/>

or scan this handy QR code.



Observations

The C1.5 (00:46 UT) and C5.2 (01:54 UT) flares of October 12, 2013 occurred between the sunspot pair of NOAA 11861. IRIS observed this region from 23:54 UT on the 11th to 03:29 UT on the 12th with a deep 30 second exposure and a dense $0.5'' \times 400$ raster, returning the full spectral readout. The slit follows flaring activity as it travels from below the east sunspot to the west sunspot.

The X1.0 flare of March 29, 2014 occurred on the northeast edge of the main sunspot in NOAA 12017 following the eruption of a filament. An 8-step “flare watch” raster with 8 second cadence was taken with the exposure length adjusted by the automated exposure control (AEC). We focus on the sequence between 17:35 UT at the onset of the filament eruption and flare to the end of the observing sequence at 17:54 UT.

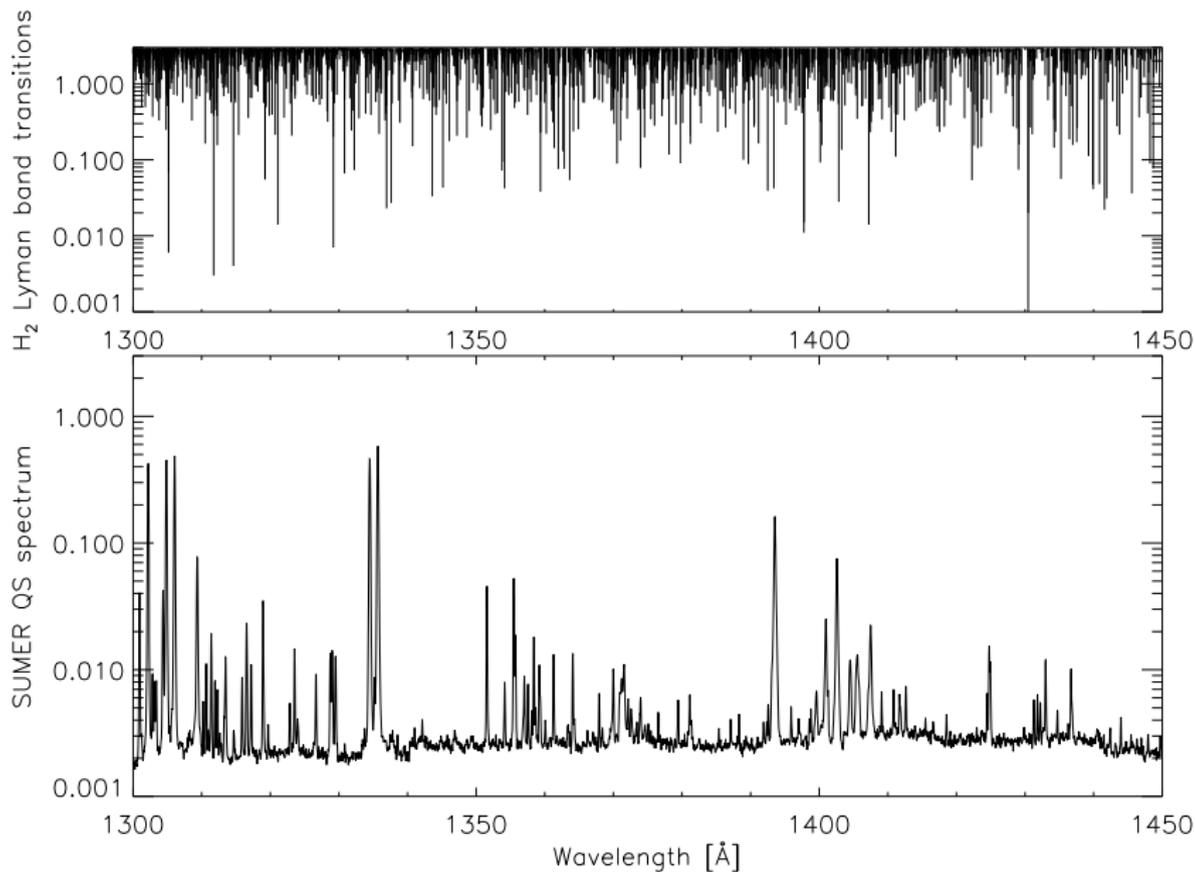
Observed H₂ lines

The flare line list has limited wavelength coverage so we have restricted our analysis to the H₂ lines at 1333.48 and 1333.80 Å in the blue wing of the C II lines. The Si IV 1394 Å line which is the primary source of excitation for these H₂ lines, was not recorded but its intensity is a constant factor of 2 greater than the Si IV line at 1403 Å which was recorded. The H₂ lines have the following parameters calculated by Abgrall et al. (1994).

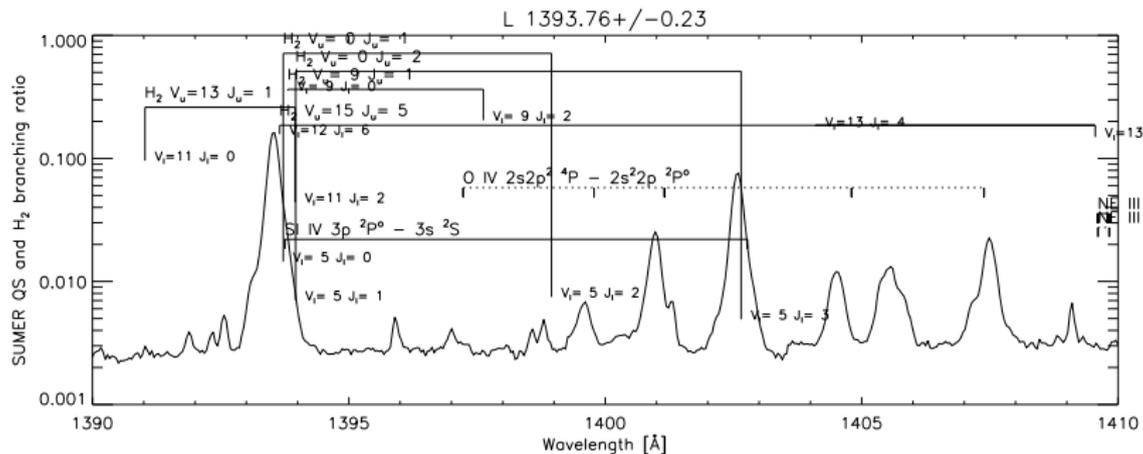
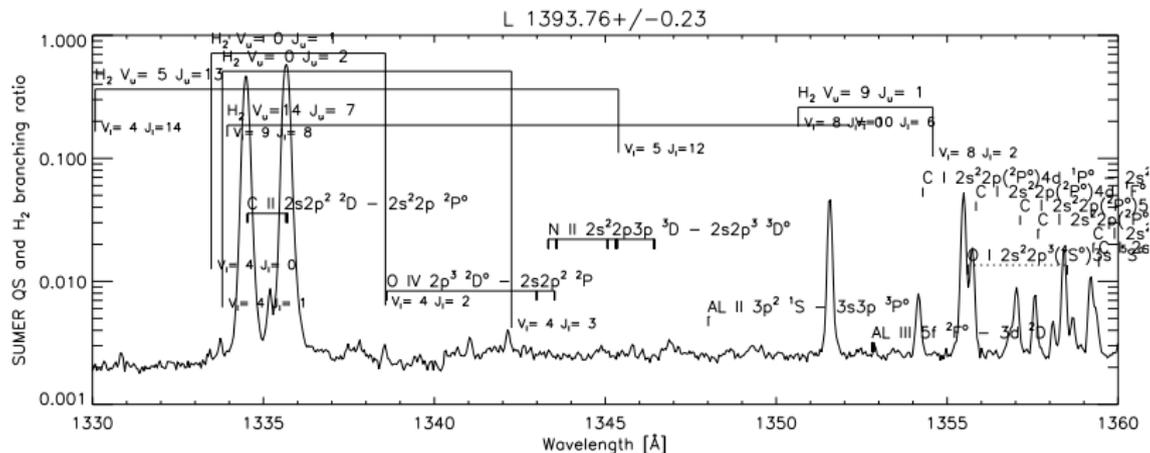
v_u	J_u	v_l	J_l	Wavelength [Å]	Branch Ratio	Exciting Line
0	1	5	0	1393.719	0.07267	Si IV 1393.775
0	1	4	0	1333.474	0.08292	
0	2	5	1	1393.961	0.08835	Si IV 1393.775
0	2	5	3	1402.648	0.12617	Si IV 1402.770
0	2	4	1	1333.797	0.10110	

The red-ward H₂ line has an upper level which is populated by both Si IV lines. It may also be blended with a S I line at 1333.80 Å. More extensive plots of the possible H₂ lines within the IRIS range are shown in the next few pages.

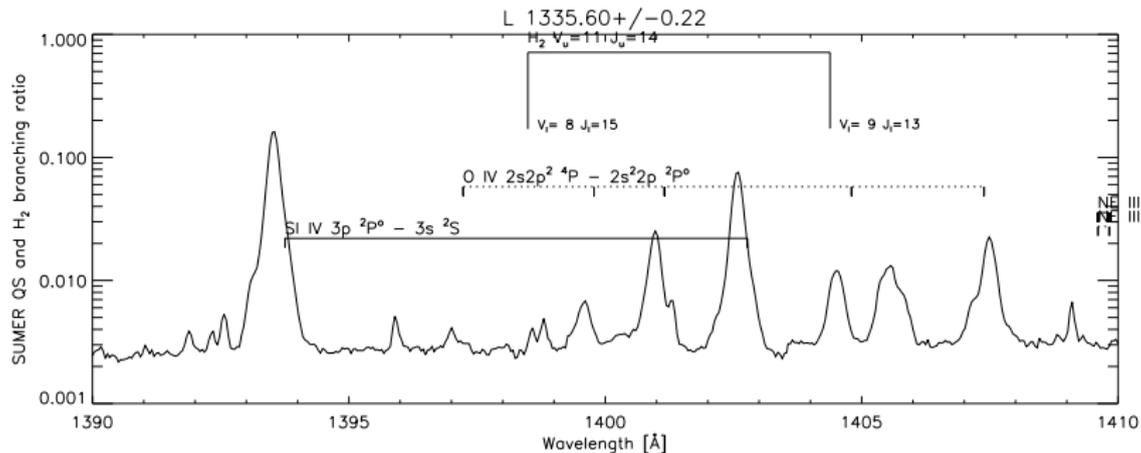
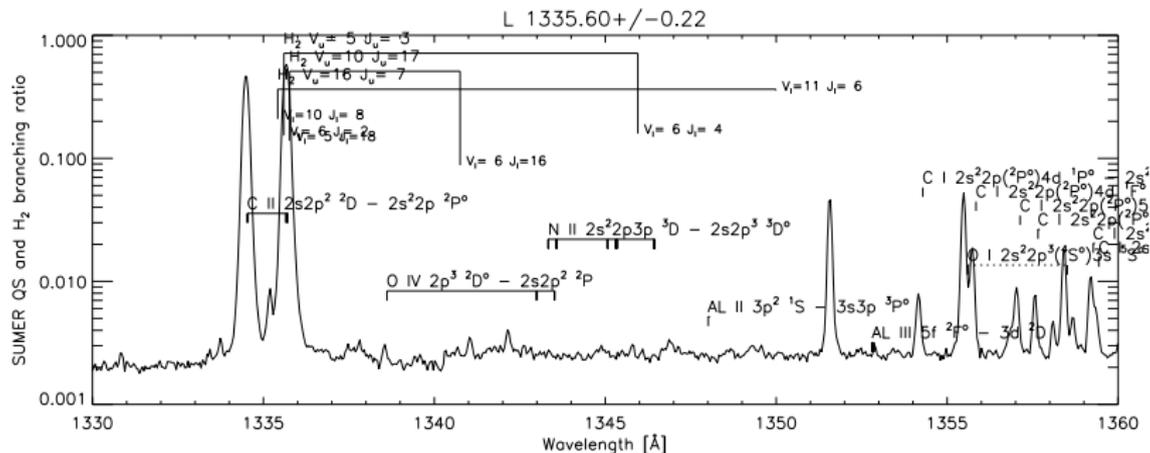
The Lyman band has on average 19 lines/ \AA in the UV.



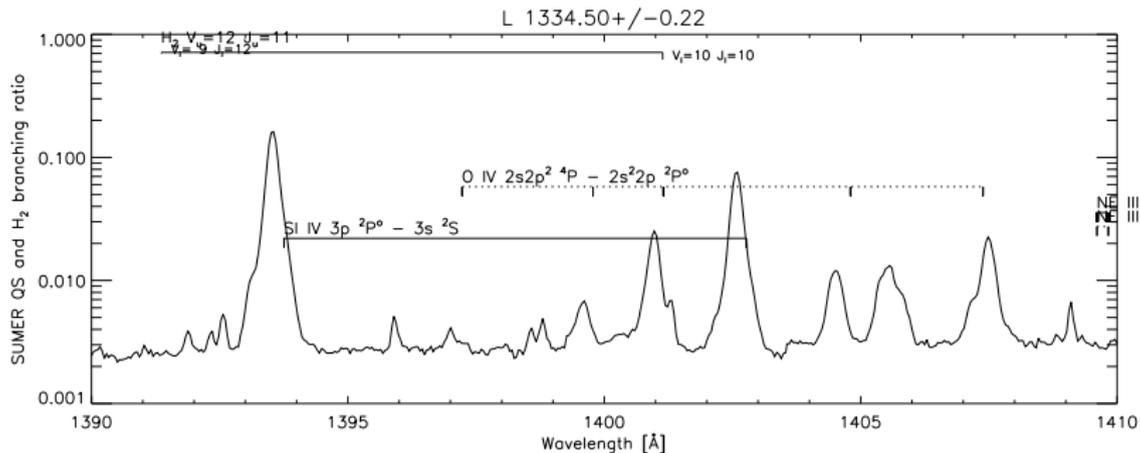
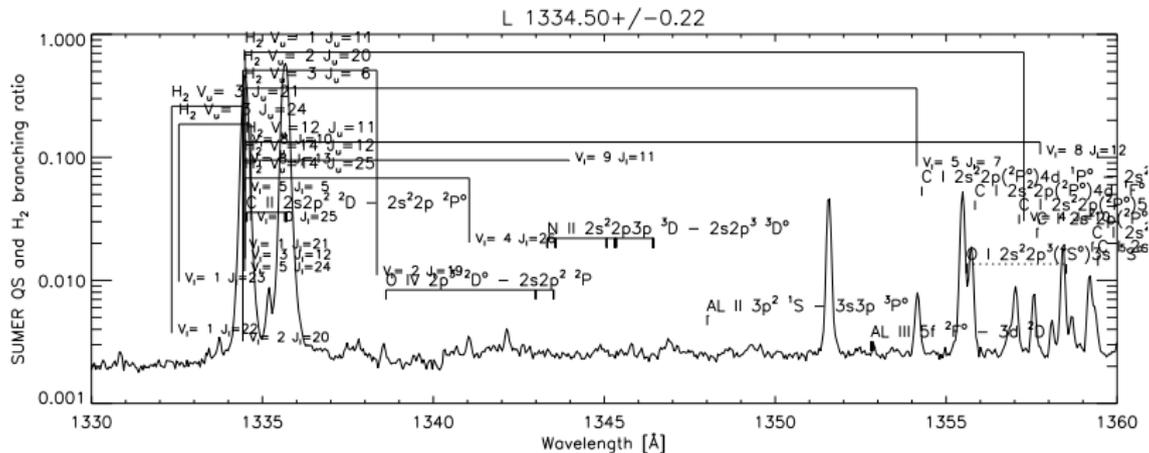
Lines excited by Si IV 1393



Lines excited by C II 1335



Lines excited by C II 1334



Analysis

For each observation we obtained the processed level 2 IRIS data. The level 2 data has been dark subtracted, flat-fielded, de-warped for spectral geometry, and each spectrum has been co-aligned with the slit jaw image (SJI). The FUV spectra are also corrected for the visible light background. The velocity calibration is not absolute, so line velocities are considered relative to a local standard of rest.

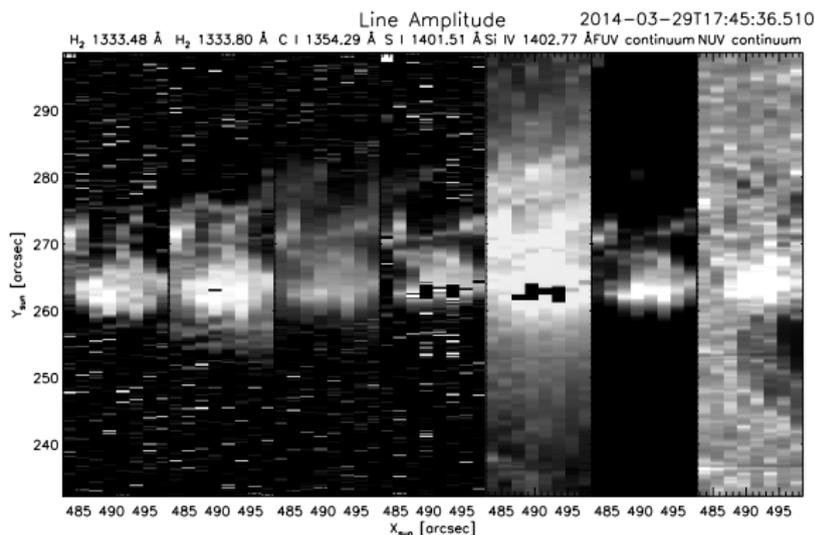
For the X flare observation, spectral lines of H₂, Si IV, and additional line and continuum parameters were determined from level 2 IRIS data. The details of the fitting are as follows:

- H₂** Each H₂ line was fit separately using a 5-term Gaussian function to account for the unevenly shaped “continuum” from the C II lines.
- Si IV** The Si IV line at 1402.77 Å was not fit with a function because its shape is often non-thermal or shows multiple components. Instead the peak amplitude, center of mass, and total flux of the line were measured. Its width given below is flux/amplitude.

- C I** The C I line at 1354.29 Å was fit to provide a velocity reference for the low chromosphere. A double Gaussian fit was performed for C I and its neighboring Fe XXI line which appears prominently in the flare and interferes with the C I fit if it is not accounted for.
- S I** A strong S I line at 1401.51 Å was fit as a reference for the blended H₂ line. A double Gaussian fit was also used for the S I line and its broad neighboring O IV line.
- Fe I** As a reference for the photospheric velocity, a clean photospheric line in the Mg II line wing near 2815.20 Å, assumed to be an Fe I line, was fit using a 5-term Gaussian function. This line vanishes during some parts of the flare, but otherwise appears to be a reliable velocity reference.
- Continua** The average continuum levels were measured in apparently line-free regions near 1400 Å in the FUV and 2826 Å far out in the Mg II line wing in the NUV.

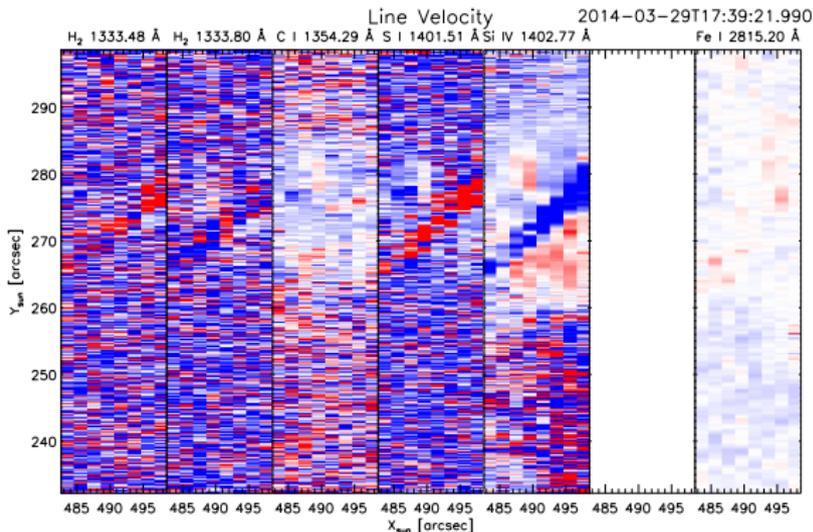
X Flare Morphology

This figure shows the log-scaled amplitudes from the line fits at the peak of the X-flare, the full movie is available on the web. Continuum intensity is high in both the FUV and NUV continua (which is not log-scaled) at the peak of the flare. The H₂ emission follows the general behavior of other lines during the flare, which seems to move from west to east across the raster.



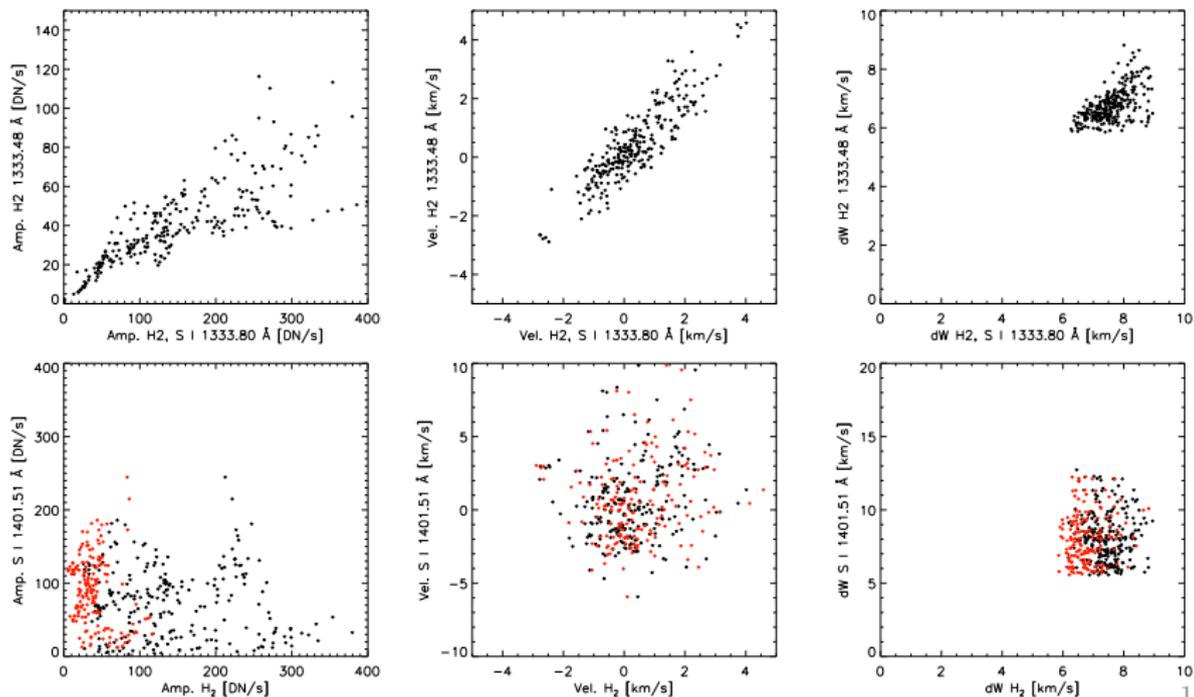
X Flare Filament Eruption

The filament eruption before the flare is clearly visible as a strong blueshift of up to 400 km/s in the Si IV line, but redshifts are apparent in the S I and H₂ lines while C I curiously shows no high velocity component. The velocity for H₂ and the neutral lines are scaled ± 10 km/s, while Si IV is scaled ± 50 km/s. A movie is also available on the web.



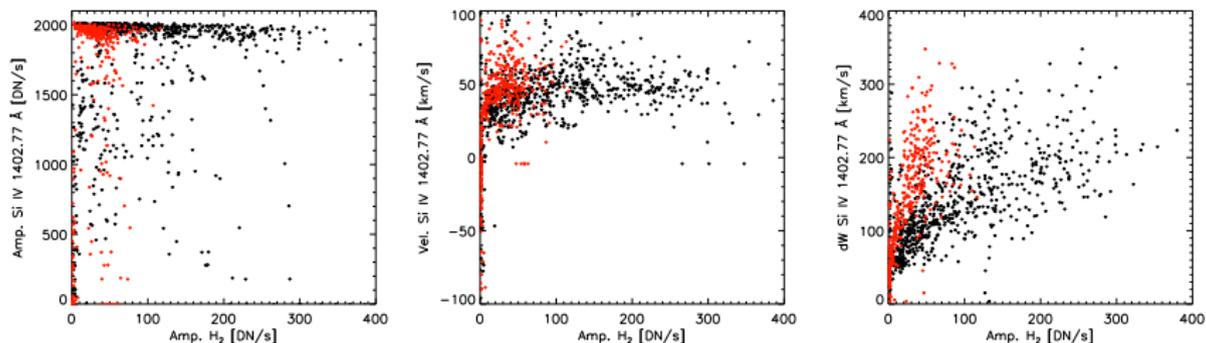
Properties of H₂ and S I lines compared

The H₂ line at 1333.48 Å and the H₂/S I blend at 1333.8 Å show similar behavior in intensity, velocity, and width. Neither the H₂ (red points) or H₂/S I blend (black points) match the behavior of the strong S I line at 1401.51 Å very well. It can be concluded that the S I line at 1333.80 Å is not strong and does not contaminate the H₂ line.



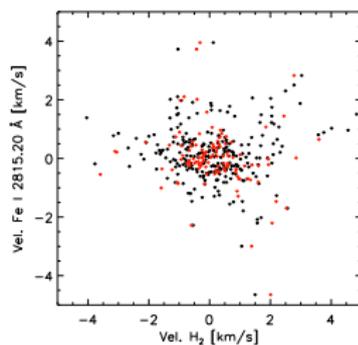
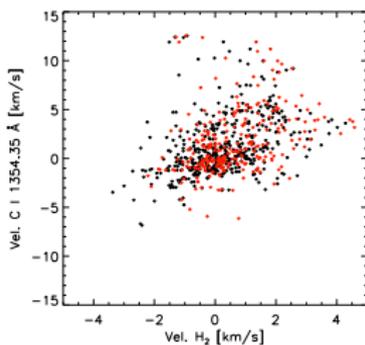
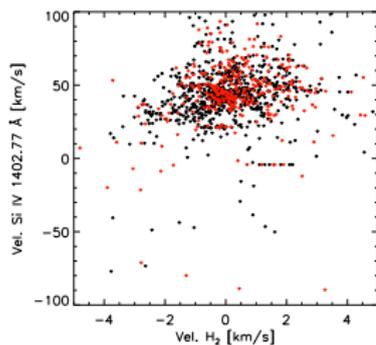
Properties of H₂ and Si IV compared

The Si IV line is easily saturated during the flare, and although the exact relationship with the H₂ intensity is difficult to determine because of this, it is clear that H₂ emission is strong where Si IV is bright. H₂ emission is also brighter where the line is broad (probably because the line is also brighter when it is broad). The H₂ lines also appear to be slightly brighter when the Si IV line is more redshifted, which seems strange because the sympathetic H₂ transitions which populate the upper level are located in the blue wing of the Si IV lines.



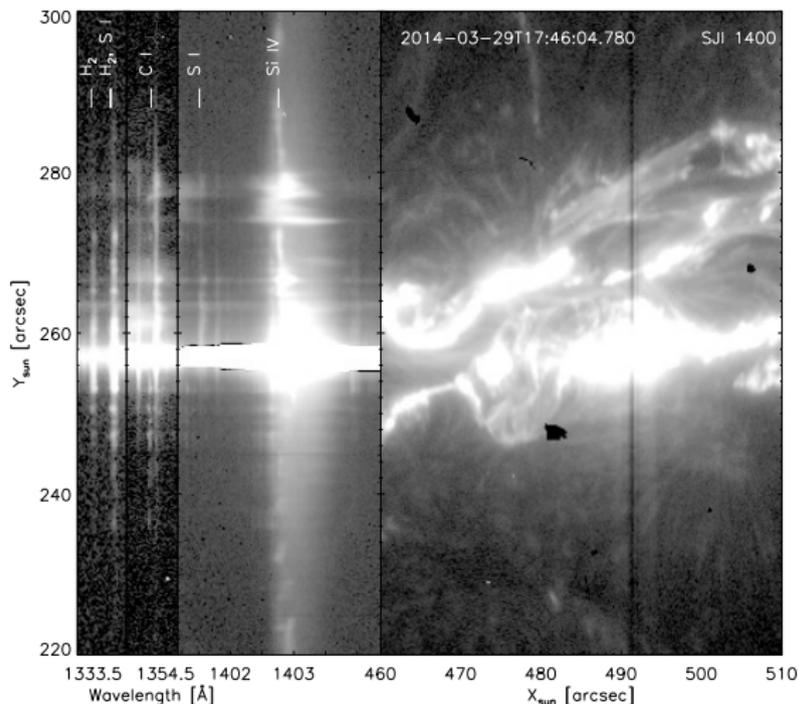
Velocity of H₂ and other lines compared

By comparing the velocity of various lines we can determine if the H₂ is closely coupled with gas in another part of the chromosphere or photosphere. A slight positive correlation is apparent between H₂ and C I, the main body of points indicates a relationship which is approximately 1:1.



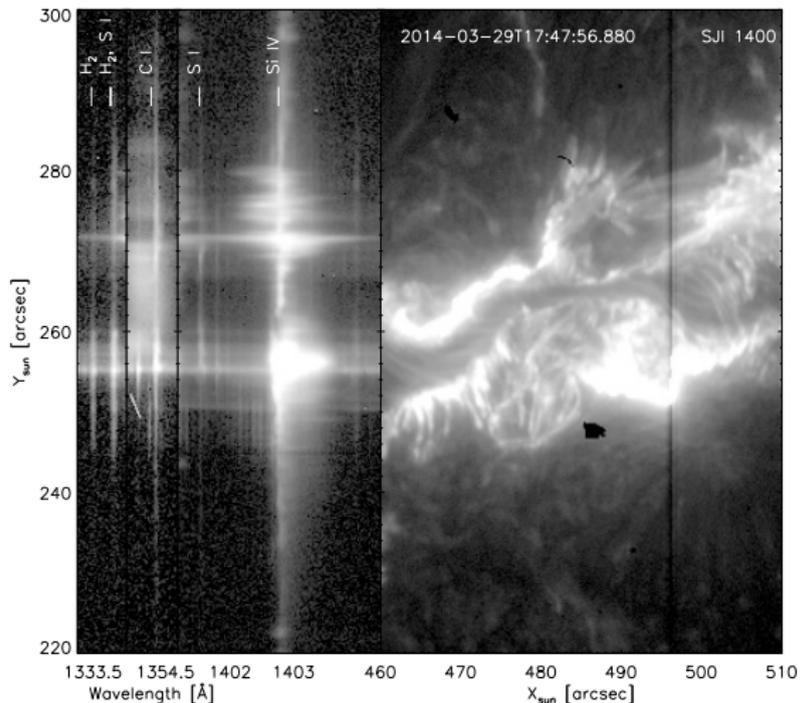
Irregular H₂ Emission

The H₂ lines (and several others) show irregular intensity along the slit a few times during the flare, with features down to the resolution limit of IRIS. The Si IV line shows fairly low, uniform level of emission over the same region. The bright Si IV in the flaring region is clearly providing the radiation for the H₂ in the region south of the flare ribbon, but intervening material with higher opacity may be blocking the H₂'s line of sight to the flare in some places, akin to seeing through tall grass, creating this clumpy appearance in the line.



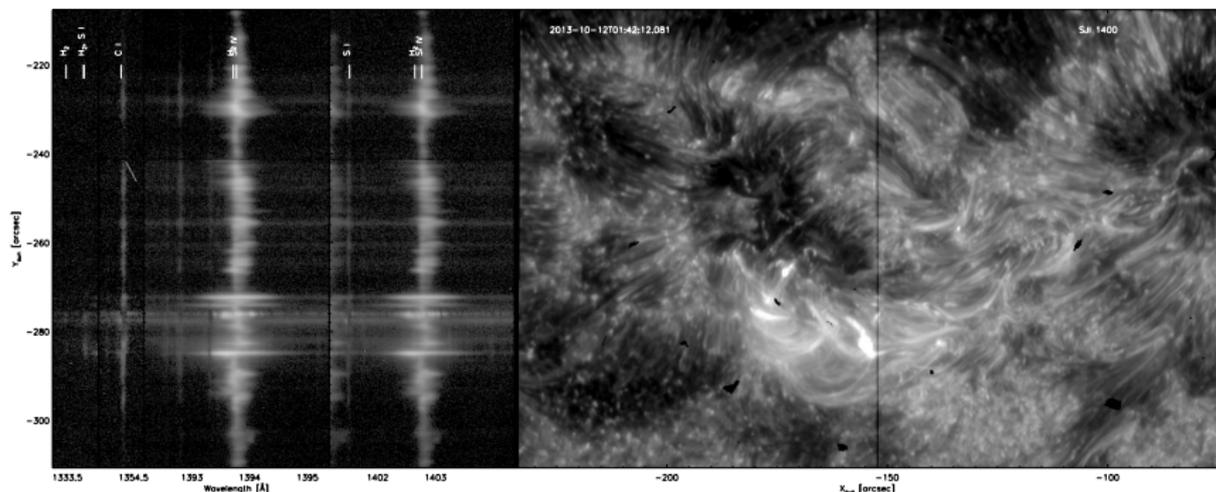
Smooth H₂ Emission

At a similar position later in the observation, the H₂ shows smooth structure. The H₂ lines also remain bright beyond the edge of the flare ribbons in a region overlying the sunspot. The lower opacity above the sunspot may allow more photons from the neighboring regions where Si IV is bright to penetrate into the sunspot atmosphere where cooler temperatures also allow for a larger H₂ population.



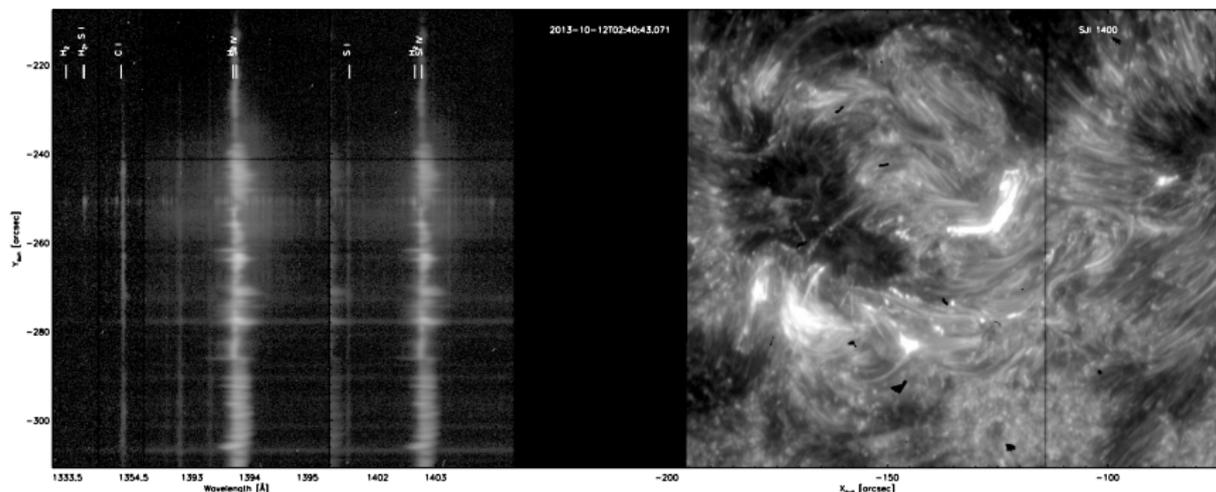
Lines in Absorption

The C-class flares of Oct 12, 2013 show very different spectra from those displayed by the X-class flare. Cool lines often appear in absorption on top on the continuum and on the wings of the bright lines, indicating that there is either cool material up high, or hot material down low in the chromosphere. Even the H_2 lines are apparent in absorption, such as the line near 1404 Å during this scan step. The lines which populate the upper levels of the 1333 Å H_2 lines may also be seen faintly in absorption, which should give a good idea of the spectral cross-section for absorption.



Hole in Opacity

At a fairly innocuous position in the Oct 12, 2013 flare raster displays a very unexpected spectrum. The Si IV lines are very weak at this position, but H₂ emission is seen alongside other unidentified lines (some of which are probably also H₂). The H₂ lines which are typically responsible for populating the upper level in the blue wing of the Si IV lines can also be seen in emission. The nearby flaring loop appears to be responsible for illuminating this pocket which may be a hole in the chromospheric opacity, allowing UV photons into a region where H₂ is more abundant.



Conclusions

- ▶ In addition to being present in sunspots, H_2 appears to be ubiquitous in the quiet-Sun, and can appear when the radiation field is sufficiently bright (as in flares) even though the abundance is low.
- ▶ H_2 appears to be coupled to the low chromosphere as revealed by comparison with the velocity of C I. Improved velocity measurement can be achieved with one of the stronger and cleaner neutral lines of C I, O I, or Cl I.
- ▶ Especially during flares, the illumination of H_2 may be non-local.
- ▶ The chromosphere's opacity in the UV plays a large role in the illumination of H_2 .
- ▶ H_2 appears to be present in filaments. It may be interesting to look for it in prominences where the local Si IV emission is low.

Abundances derived from observations to be established through detailed modeling of the low chromosphere, taking into account the effects of pressure on H_2 formation, how the opacity in the UV modifies the radiation field, and the possibility of non-local illumination. An easier task may be spectral synthesis based on atmospheric models and simulations, which will be the next step in this work.

References and Acknowledgements

- Abgrall, H. et al., 1994, *Can. J. Phys.*, 72, 856
De Pontieu, B. et al., 2014, *Sol. Phys.*, 289, 2733
Jaeggli, S. A., Lin, H., & Uitenbroek, H., 2012, *ApJ*, 745, 133
Jordan, C. et al., 1977, *Natur.*, 270, 326
Jordan, C. et al., 1978, *ApJ*, 226, 687
Bartoe, J.-D. F. et al., 1979, *MNRAS*, 187, 463

Many thanks to Davina Innes for her keen inspection of the IRIS data and useful discussions about H₂, and to Charles Kankelborg for his enthusiasm and spellchecking.

The work of S. Jaeggli was supported under IRIS contract from Lockheed Martin to MSU, and the work of S. Saar was supported under IRIS contract SP02H1701R from Lockheed Martin to SAO.