Astron. Astrophys. 361, L60–L62 (2000)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Detection of the H I n=22–21 Rydberg line in emission at the solar submillimetre limb

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Received 10 August 2000 / Accepted 4 September 2000

Abstract. This letter reports the discovery of excess emission at the position of the H I n=22–21 Rydberg transition in submillimetre solar spectra taken at the extreme solar limb. This emission feature at 22.096±0.003 cm^{-1} shows significant limb brightening, reaching intensities of 11% above the adjacent spectral continuum with line shapes fitted best by Gaussian functions with widths of 0.018±0.004 cm^{-1}. This measurement represents the highest-n Rydberg line of H I detected to date in the solar spectrum.

Key words: line: identification – Sun: atmosphere – Sun: general – Sun: infrared

1. Introduction

Atomic lines from Rydberg transitions in H I and heavier elements in the Sun, particularly Mg I and Si I, have now been detected from atomic levels as high as n=20–19 (Clark et al. 2000 and references therein). Lines from these transitions change from absorption at lower n to emission at higher n, and exhibit significant limb brightening, particularly at higher-n levels. Although theoretical modelling has successfully explained the detailed characteristics of the Mg I features (Carlsson et al. 1992; Chang et al. 1991), only the general behaviour of the H I lines has been reproduced. The limitation arises from the difficulty of modelling the highly structured source region of the H I lines in the low chromosphere (Carlsson & Rutten 1992).

We recently reported the first detection of the n=20–19 transition of H I in the Sun at 29.622 cm^{-1} using a Fourier transform spectrometer (FTS) at the James Clerk Maxwell Telescope (JCMT) (Clark et al. 2000). The present letter describes the first detection of the n=22–21 transition at 22.095 cm^{-1} from the JCMT using this same observational technique.

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2. Instrumentation and observations

The instrumentation for these observations was similar to that used in the detection of the H I n=20–19 line (Clark et al. 2000). The polarising interferometer used in the previous measurements was reconfigured as a classical Michelson interferometer to exploit the increased efficiency provided by newly developed intensity beamsplitters (Ade et al. 1999). In addition to the increased efficiency, this non-polarising beamsplitter ensured that these measurements were not sensitive to the polarisation of Zeeman components of solar spectral features. The FTS was operated in rapid scan mode and produced spectra with a resolution of 0.005 cm^{-1} (5 mK) in a scan time of one minute.

The observations were made on the morning of 1999 December 18. Spectra were acquired in the following sequence: one at disk centre, one at a background sky position 2000″ from disk centre, and two at a selected limb position. This cycle was repeated for various limb positions on the positive-azimuth side of the Sun, and the entire observing sequence was then repeated on the negative-azimuth side of the Sun. All beam offsets were made in azimuth to maintain constant airmass for each set of solar and sky spectra. The Sun contained three major sunspot groups at the time of observation. Careful mapping of the observing positions on an H_α image of the Sun taken at a time almost coincident with the present observations showed that the positive-azimuth sequence of observations sampled a quiet solar limb. The negative-azimuth sequence sampled spectra along a track which came close to, but avoided, a large active region which had recently appeared over the east solar limb.

3. Data analysis

The interferograms were processed using standard Fourier transform spectroscopic techniques, as described in Clark et al. (2000). The precise position of each limb measurement was determined from the symmetry of continuum intensity profiles from each limb of the Sun. Corresponding background spectra were subtracted from all limb and disk-centre spectra. Fig. 1

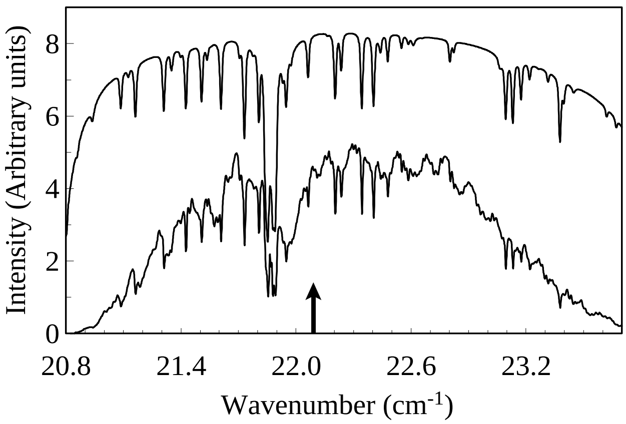

Fig. 1. The lower curve represents the average of three disk-centre spectra, after subtraction of the corresponding background spectra. A synthetic atmospheric transmission spectrum, calculated for Mauna Kea and convolved to the spectral resolution of the interferometer ($0.005\,cm^{-1}$), is superimposed for comparison (upper curve). The overall shape of the measured spectrum is controlled by a cooled bandpass filter, which is not included in the synthesis. The location of the H I n=22–21 feature is indicated.

shows an average of three such difference spectra for the disk centre position along with a synthetic atmospheric transmission spectrum calculated for Mauna Kea using the spectral modelling program FASCOD (Anderson et al. 1996). The transmission spectrum has been convolved to a resolution of $0.005\,cm^{-1}$ to match the measured resolution of the interferometer (Naylor et al. 2000).

The structure in the measured spectrum in Fig. 1 arises from several sources: line absorption by atmospheric O_2 and O_3, line and continuum absorption by atmospheric H_2O, the transmission characteristic of the bandpass filter, and channel fringes generated by resonant optical cavities in the detector system. The combination of these effects, and their variability, makes identification of weak spectral features in the disk-centre solar spectrum difficult. We therefore searched for the presence of a limb-brightened feature due to the n=22–21 transition of H I using the method of Clark et al. (2000), with which we detected the n=20–19 transition by comparing limb and disk-centre spectra.

The emission feature was extracted from each background-corrected limb spectrum by subtracting from it a scaled, background-corrected disk-centre spectrum, where the scaling factor was chosen to compensate for overall variations in atmospheric transmission between limb and disk-centre spectra and for the partial filling of the telescope beam when viewing the solar limb. The small residual baseline was then removed by spline-fitting to neighbouring regions of the difference spectrum. The resulting spectra from different positions on the positive-azimuth side of the Sun are shown in Fig. 2. Standard spectroscopic fitting algorithms (GRAMS/32, Galactic Industries Corp.) were used with fully variable fitting parameters to extract positions, heights and widths of the detected emission features.

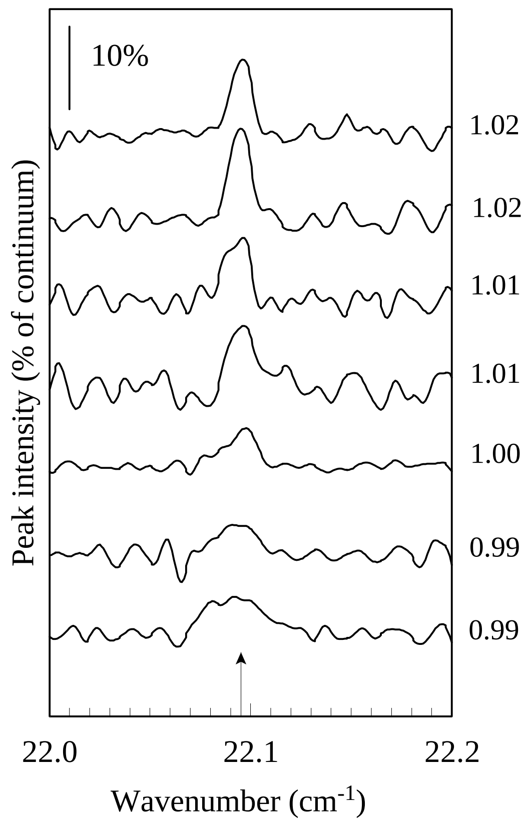

Fig. 2. A sequence of 7 difference spectra between limb and corresponding disk-centre spectra is shown. Observing position for each limb spectrum, described by distance from disk-centre as a fraction of submillimetre solar radius, is shown to the right of each graph. The vertical scale of each spectrum is indicated at top left. The H I n=22–21 emission feature at $22.095\,cm^{-1}$ is clearly evident.

4. Results and discussion

A narrow and distinct emission feature was evident in all limb spectra taken at than 950″ from disk centre on either side of the Sun during this run. The detections were unambiguous in data from the early part of the run but were less clear in later spectra due to deterioration of the weather above the telescope, as evidenced by a marked increase in the amount and variability of atmospheric water vapour. The mean position of the detected features is $29.096\pm0.003\,cm^{-1}$, which agrees well with the H I n=22–21 transition at $22.095\,cm^{-1}$.

Fig. 3 shows the limb-brightening curve of the peak intensity of the H I feature. Intense limb brightening is evident very close to the limb. Each of these measurements represents a convolution of line emission over the solar disk with the beam pattern of the telescope, centred at the appropriate limb position. Data points which are apparently off the Sun actually represent samples of the extreme solar limb by the wide telescope beam, the central core of which was measured in the present experiment to be 19″ (FWHM). This limb brightening curve agrees well with that observed for the n=20–19 transition of H I (Clark et al. 2000), showing a sharper rise at the limb which reflects the narrower beam pattern of the present observations.

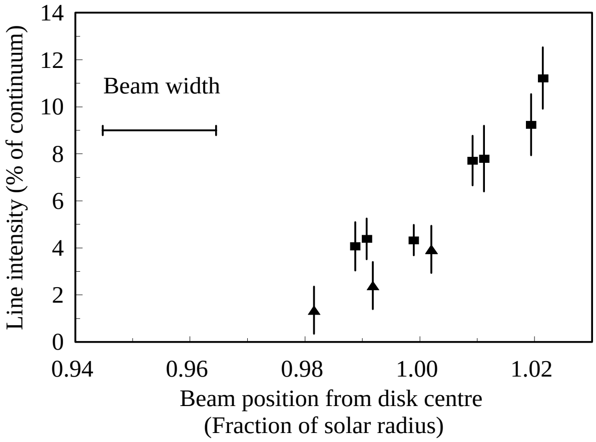

Fig. 3. Peak height of the H I n=22–21 emission feature as a function of the position of the centre of the telescope beam, represented as a fraction of the submillimetre solar radius (979′′). Measurements on the positive-azimuth and negative-azimuth sides of the Sun are denoted by squares and triangles, respectively. The points which lie beyond the limb represent the sampling of the extreme limb by a portion of the wide telescope beam (width indicated).

As previously discussed (Clark et al. 2000), the line fitting procedure adopted in this analysis is sensitive to the assumed baseline and conceals any wide Lorentzian wings which may be present. The detected feature is then only the central core of the emission line, and was best fitted by a Gaussian function. The average width of the line core was found to be 18$\pm$4 mK, and no significant variation with limb position was seen. This is significantly smaller than the 45 mK value predicted by Hoang-Binh for ion-broadened Lorentzian lines in his original paper (1982), and even further below his more refined prediction of 50 mK in a later paper (1987). It is interesting to note that the widths of this and the n=20–19 transition (24$\pm$7 mK; Clark et al. 2000) are in direct proportion to their frequencies, as would be expected for a Doppler-broadened line, even though these widths are both an order of magnitude larger than the theoretical Doppler width at the temperature of the emitting region ($\sim$7000 K).

5. Conclusions

The H I n=22–21 Rydberg line has been detected for the first time as excess emission at the limb of the Sun. Intense limb brightening has been observed, in agreementwith that measured for the the n=20–19 line (Clark et al. 2000). The width of this feature is consistent with the width of the n=20–19 line. This measurement represents the highest-n Rydberg line detected to date in the solar spectrum and places a further constraint on models of the lower chromosphere.

Acknowledgements. It is a pleasure to thank G.J. Tompkins for his support and assistance during this observing run and Dr. P.A.R. Ade for the generous provision of the beamsplitter used in this experiment. The authors thank the director of the JCMT for discretionary time for this programme. DAN and GRD were recipients of NSERC Research Grants during this work and acknowledge this invaluable support. The James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organization for Scientific Research and the National Research Council of Canada.

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