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VARIATIONS OF THE HYDROGEN LYMAN-ALPHA LINE THROUGHOUT SOLAR CYCLE 24 ON ESA/PROBA-2 AND SORCE/SOLSTICE DATA

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Abstract

The hydrogen Lyman-Alpha (Ly-α) spectral line (121.567 nm) is of importance for studying the solar atmospheric ultraviolet flux variability. We present high resolution spectral observations of the Ly-α line carried with the LYRA scientific instrument onboard the ESA/PROBA-2 mission. We followed the variations of the shape of the hydrogen Ly-α line through solar cycle 24 and compared LYRA with SOLSTICE data highlighting significant differences in their behaviour. Although we used level 2 of LYRA data, an important degradation effect is still affecting the data preventing accurate studies of long-term variations of the solar irradiance.

Key words: hydrogen Lyman-Alpha (Ly-α), LYRA, ESA/PROBA-2 mission, SOLSTICE, NASA/SORCE experiment

1. Introduction. Solar far ultraviolet (FUV) and extreme ultraviolet (EUV) irradiance affect the Earth's upper atmosphere by heating, exciting, dissociating and ionizing its main constituents. The resonance solar hydrogen Lyman-Alpha (Ly-α) line (121.567 nm) is the strongest line in the solar spectrum and is of particular importance for its impact on the Earth's atmosphere [1], ionosphere and exosphere [2,3]. The lower ionosphere (50–100 km above the earth's surface) is created by the most penetrating radiation, which is very sensitive to solar

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activity. Analysis of the conditions of absorption of the solar radiation shows that the Ly-α line ionizes the nitric oxide NO in the upper atmosphere. In fact, the Ly-α line, along with X-rays and cosmic rays, are factors for the formation of lower ionosphere of the Earth [4,5]. At higher altitudes, above 100 km, the contribution of the the Lyman-Beta (Ly-β) line (102.572 nm) is important and dominant [3].

Observations in Ly-α hours before a flare event or a filament/prominence eruption, can provide precious precursor indications (better than the He II line, well suited only for limb observations) because its superior contrast and resolution help to evidence field lines for modelling [6]. Indeed, Ly-α line is very sensitive to flares as shown by observation [1] with LYRA/PROBA-2 of the rising phase of a M2.0 flare that reached almost 1% of the integrated flux of the whole solar disk. Beside this very high sensitivity to flares and variations of temperature in the chromosphere, it is also sensitive to velocities and magnetic fields [7]. Line-integrated solar Ly-α irradiance variations have been measured by several satellites beginning in the 1960's with Orbiting Solar Observatory OSO 4 (1967–1969), OSO 5 (1970–1975), OSO 6 (1969), AEE (1977–1980), SME (1981–1989), San Marco (1988), up to Upper Atmosphere Research Satellite UARS (1991–1997), and showing that Ly-α irradiance varies according to the activity of magnetic field groups [8].

Lemaire et al. [9] studied the full Sun Ly-α and Ly-β profiles during solar cycle 23 using the SUMER spectrometer onboard the SOHO (Solar and Heliospheric Observatory) satellite. In addition, in [10] a relationship is obtained between the central and the total solar Ly-α irradiance directly derived from full-Sun H I Ly-α solar profiles obtained also by SUMER/SOHO during solar cycle 23. As mentioned earlier, [1] showed that LYRA is a suitable instrument to observe the Ly-α emission during flares in cycle 24.

Several instruments as SOLSTICE and SUSIM onboard UARS monitored the ultraviolet irradiance from 119 nm to about 420 nm, from 1991 to 2005. The objective of these instruments was to access the variability on mid- and long-term intervals (e.g. solar cycle) of the irradiance in that spectral range. These are the only two detections of a Lyman-Alpha flare in full-Sun fluxes prior to the LYRA observations [1]. LYRA acquires solar-irradiance measurements providing time series of solar irradiance with a very high sampling cadence (up to 100 Hz) in spectral ranges from soft X-ray to UV, that have been chosen for their relevance to solar physics, space weather and aeronomy [11].

2. Purpose of the study. The main objective of this study is to give a more comprehensive view of the variability of the solar irradiance on an as long as possible time range (e.g. solar cycle in the best case) in the very important Ly-α line. In this paper, first, we compare the irradiance of the Ly-α line from LYRA with the Ly-α irradiance from SOLSTICE during the rising phase of the solar cycle 24 (from 2010 to 2014). Then, by using LYRA data, we choose disturbed and quiet days for different months in 2010 to see if flare events affect Lyman-

Alpha observations.

After downloaded raw data (fits file) for both instruments in counts are converted back to counts ms^{-1}, we use IDL procedures to read the data.

3. Observations and data set. ***3.1. The Large-Yield RAdiometer (LYRA) instrument.*** PROBA-2 (PRoject for On-Board Autonomy-2) [12,13] is a small ESA satellite that launched on November 2, 2009, in order to explore the Sun activity and its effect on Space Weather. PROBA-2 is orbiting in a heliosynchronous orbit at an altitude of 725 km. It has two main instruments: the Sun Watcher using an Active Pixel system detector and image processing (SWAP) telescope and the Large Yield RAdiometer (LYRA).

LYRA/PROBA-2 is a vacuum ultraviolet (VUV) solar radiometer [14], monitoring the Sun in four spectral bands that range from UV to soft X-ray. LYRA (dimensions: $315 \times 92.5 \times 222$ mm^3) consists of three identical units, but not technically identical [11]. One of these units (unit 2) is used quasi-permanently, while the two other units (units 1 and 3) are used for monitoring the degradation and for specific observation campaigns [15].

Each one of them has the same four broad spectral bands which are chosen for their relevance to Solar Physics, Aeronomy and Space Weather [16]. The four channels (wavelength bands) are:

1. Lyman-Alpha channel (120–123 nm).
2. Herzberg continuum channel (190–222 nm).
3. Aluminum filter channel (17–80 nm).
4. Zirconium filter channel (6–20 nm).

LYRA data produces time series of spectral irradiance in its four bandpasses in a quasi-uninterrupted way. As mentioned above, LYRA consists of three identical units; the reasons for this strategy are the following [17]:

- **Unit 2 (permanent use)** is used quasi-permanently but it is therefore the most affected by degradation. The degradation is so strong that the solar signal is now barely detectable in the Ly-α and Herzberg channels.
- **Unit 3** is used in a campaign-driven way and keeps its cover closed the rest of the time, limiting ageing effects.
- **Unit 1 (reference unit)** acquires data for 40 minutes every three months. It is used as a reference to calculate the degradation of units 2 and 3.

LYRA data are available within four hours after their acquisition. It is produced in 5 different processing levels:

- (Level 1): raw, uncalibrated data.
- (Level 2): calibrated data converted to physical unit (W m^{-2}).
- (Level 3): level 2 averaged over 1 min data.
- (Level 4A and Level 4B): daily plot of calibrated data and every 3 days of all LYRA, quicklooks.
- (Level 5): flares list with link to LYRA and GOES flux profile.

Note that despite corrections of spacecraft, instrument and environmental effects, the calibrated level 2 and level 3 data still suffer from several instrumental effects.

3.1.1. Large Angle Rotations (LARs). The spacecraft is rotating by 90 degrees around the spacecraft-Sun axis every 25 min. That creates sharp peaks and dips in LYRA channels that are, at present, not easily correctable, as shown in Fig. 3 left panel in reference [15].

3.1.2. Stabilization after cover closing/opening. The unit 2 channels 1, 3 and 4 have diamond detectors requiring to be exposed a certain time before reacting nominally. This is because of surface defects on the detectors that trap the photoelectrons before they are collected by the electrodes. This phenomenon has effects on the measurements until all the traps have been filled. All the trapped electrons, after closing the covers, are gradually released and collected by the electrodes. So, the observed flux takes some time before reaching its real level. This effect, as shown in Fig. 3 (right panel) in reference [15], results in a slow stabilization of the flux level after the cover is closed and opened again.

3.1.3. Peak after instrument switched on or reloaded. The first data sample after switch-on or reload of the instrument has been removed because it shows undesirable behaviour as shown in Fig. 4 in paper [15]. The calibration process does not correct the data from all effects which cause fluctuations in data (as the flat-field effect, see Fig. 9 in [17]). Note, even though, that the spacecraft breaks introduce fluctuations in the LYRA signal of less than 1% only [17].

3.1.4. Correction for degradation. However, LYRA suffered a strong instrumental degradation caused by a combination of contaminants and long exposure to the Sun light that make it difficult to truly assess irradiance variations on the mid- and long terms. After the covers were opened in the first hours, affecting more seriously its longer-wavelength channels [15].

3.2. The SORCE/SOLSTICE experiment. SORCE (SOlar Radiation and Climate Experiment) is a satellite flown by NASA that provides measurements of incoming X-ray, ultraviolet, visible, near-infrared, and total solar radiation. SORCE measurements specifically address long-term climate change, natural variability and enhanced climate prediction, and atmospheric ozone and UV-B radiation. These measurements are critical to studies of the Sun and of its effect on our Earth system.

The SORCE spacecraft was launched on January 25, 2003, into a 645 km, 40 degree orbit and is operated by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado in Boulder, USA. It continued the precise measurements of total solar irradiance (TSI) that began with the ERB instrument in 1979. SORCE also provided the measurements of the solar spectral irradiance from 1 nm to 2400 nm, accounting for 96% of the spectral contribution to TSI. SORCE is to be decommissioned in January 2020 (relay taken by the TSIS-1 experiment on the International Space Station).

SORCE has four instruments:

- The Spectral Irradiance Monitor (SIM).
- SOLar STellar Irradiance Comparison Experiment (SOLSTICE).
- Total Irradiance Monitor (TIM).
- The XUV Photometer System (XPS).

For the first time in this work we explore the variations of the shape of the hydrogen Lyman-Alpha line through solar cycle 24 comparing LYRA with SOLSTICE data considering the degradation effect, which affects the data and prevents accurate studies of long-term variations of the solar irradiance.

We are interested in SORCE/SOLSTICE that is the follow-on to the very successful SOLSTICE instrument launched aboard the Upper Atmospheric Research Satellite (UARS) in 1991 [17]. SORCE/SOLSTICE measures daily solar ultraviolet (115–320 nm) irradiance and compares it to the irradiance from an ensemble of 18 stable early-type stars. This approach provides an accurate monitoring of instrument in-flight performance and provides a base for solar-stellar irradiance comparison in the future.

4. Results and discussion. The mean daily irradiance of LYRA channel 1 (Lyman-Alpha) is shown in Fig. 1–3. In order to validate these time series we compared them with the SOLSTICE data.

Figure 1 displays the comparison between LYRA channel 1 (Fig.1 a–f) (in relation between time and irradiance of Lyman-Alpha) and SOLSTICE irradiance for Lyman-Alpha

(Fig. 1 h–l) for each year during the rising phase of solar cycle 24. In Fig. 1 we notice that there are differences in the behaviour between LYRA and SOLSTICE data. For LYRA data we started comparison in February 2010 in order to avoid the instability in data caused by the start of operations. For both SOLSTICE and LYRA data in 2010 we notice that the data are almost linear. But, in 2011, the SOLSTICE data is increasing rapidly, while LYRA data are almost linear. In 2012, 2013, 2014 the SOLSTICE data are almost linear.

Note that SOLSTICE data increase every year on average of 0.052% while in LYRA data we notice that, from 2010 to 2011, the average for each year dropped by 2% and, then, only of 0.01% from 2012 until 2014. In Table 1 we calculate the average irradiance for each year during the rising phase of solar cycle 24 for both LYRA and SOLSTICE data in order to show that the irradiance of SOLSTICE is increasing while LYRA data average of irradiance is decreasing due to the instrument degradation of data. In this study we used level 2 data (calibrated data, that are corrected by subtraction of dark currents, and normally compensated for degradation). However, we found that degradation still affects the Lyman-Alpha channel. Also Fig. 1 shows the difference between LYRA data and SOLSTICE data during the rising phase of solar cycle 24 from January 2010 to December 2014. The behaviour during the rising phase of solar cycle 24 for both data is not the same. We found that for SOLSTIE data (Fig. 1l), the irradiance

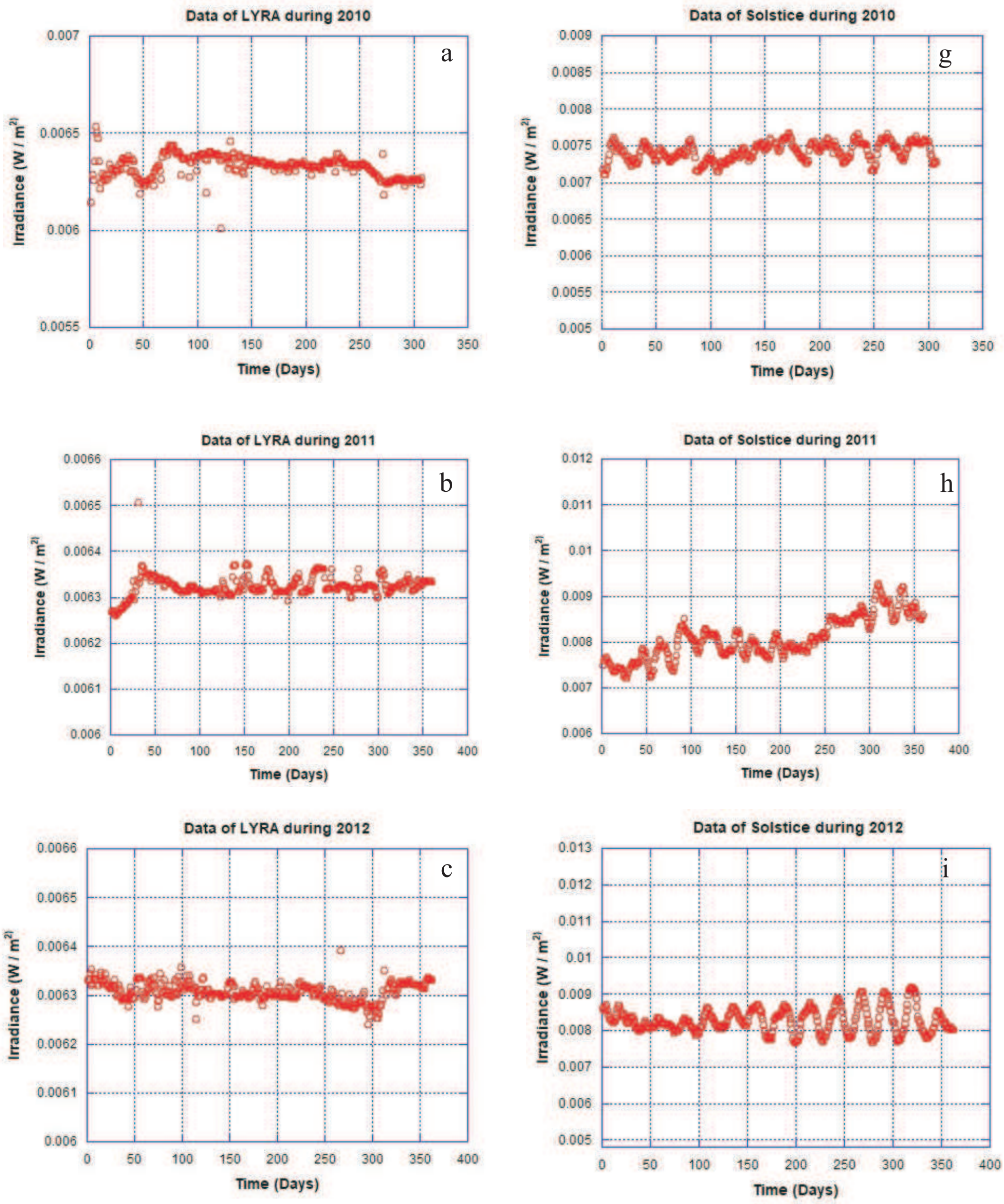

Fig. 1. The left panels show the variation of Lyman-Alpha based on the LYRA data (a–c) for each year from 2010 to 2012. The right panels show the variation of Lyman-Alpha based on the SOLSTICE data (g–i) from 2010 to 2012

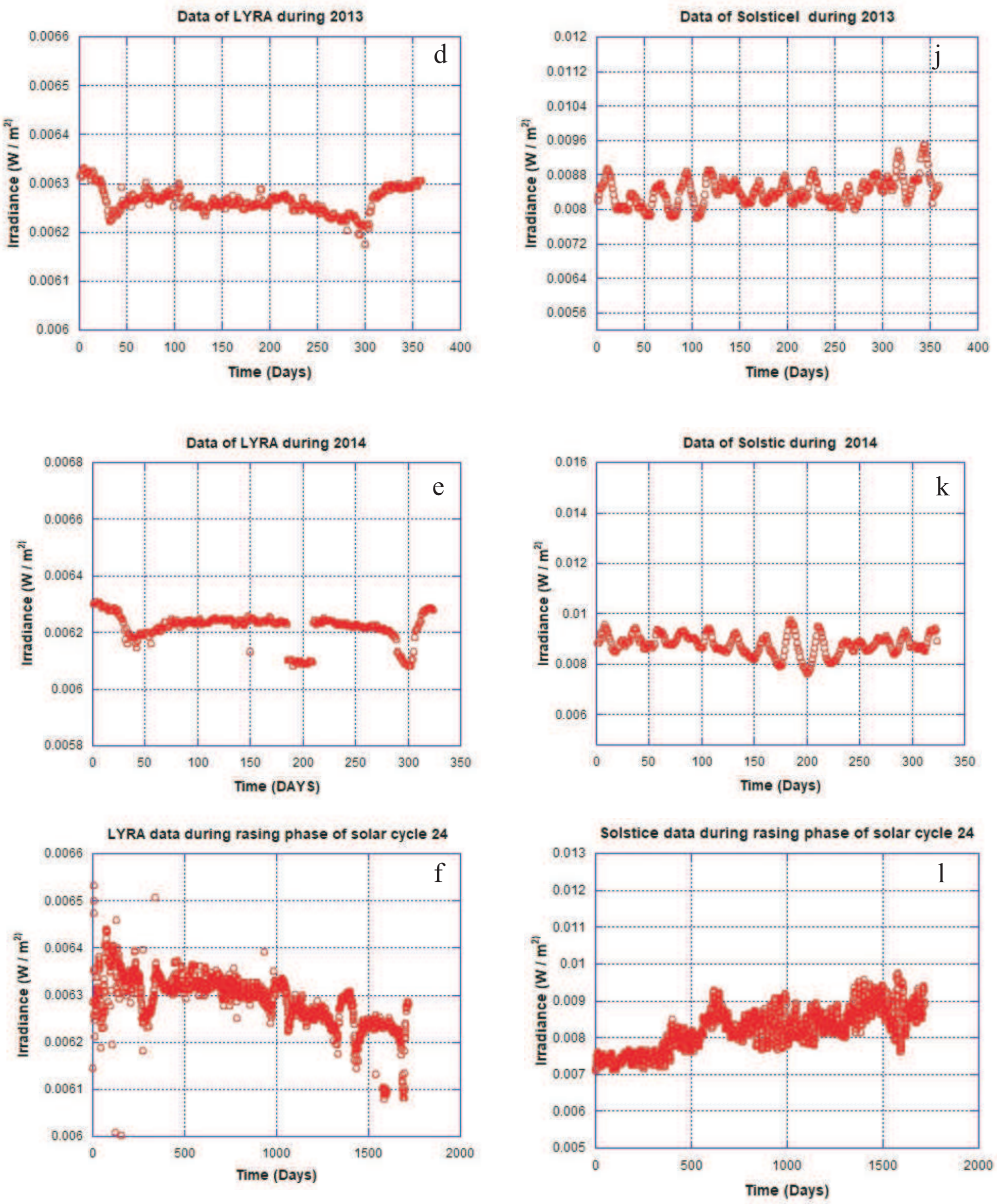

Fig. 1. The left panels show the variation of Lyman-Alpha based on the LYRA data (d, e) for 2013 and 2014. The right panels show the variation of Lyman-Alpha based on the SOLSTICE data (j, k) for 2013 and 2014. Lyman-Alpha profiles during the rising phase of solar cycle 24 (from 2010 to 2014) for both SOLSTICE data and LYRA data are also shown (f, l)

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Average irradiance for both SOLSTICE and LYRA data during the rising phase of solar cycle 24 (from 2010 to 2014)

year	Average irradiance (W/m^2) SOLSTICE Data	Average irradiance (W/m2) LYRA Data
2010	0.007404	0.03240258
2011	0.00809	0.006323854
2012	0.008293	0.006309599
2013	0.008418	0.006264
2014	0.008067	0.006218
total	**0.008204**	**0.006277**

increases during the rising phase of solar cycle 24, while for LYRA data (Fig. 1k) the irradiance decreases during the rising phase of solar cycle 24 (see Table 1).

To check if LYRA data is effective in studying data on shorter terms, we chose a 2010 sample to investigate if flare events will affect Lyman-Alpha channel. We selected a quiet day and a disturbed day: quiet day February 25, 2010 (Fig. 2a); disturbed day February 7, 2010 that experienced 13 flare events (Fig. 2b).

In Fig. 2 the top panel displays both quiet day (Fig. 2a) and disturbed day

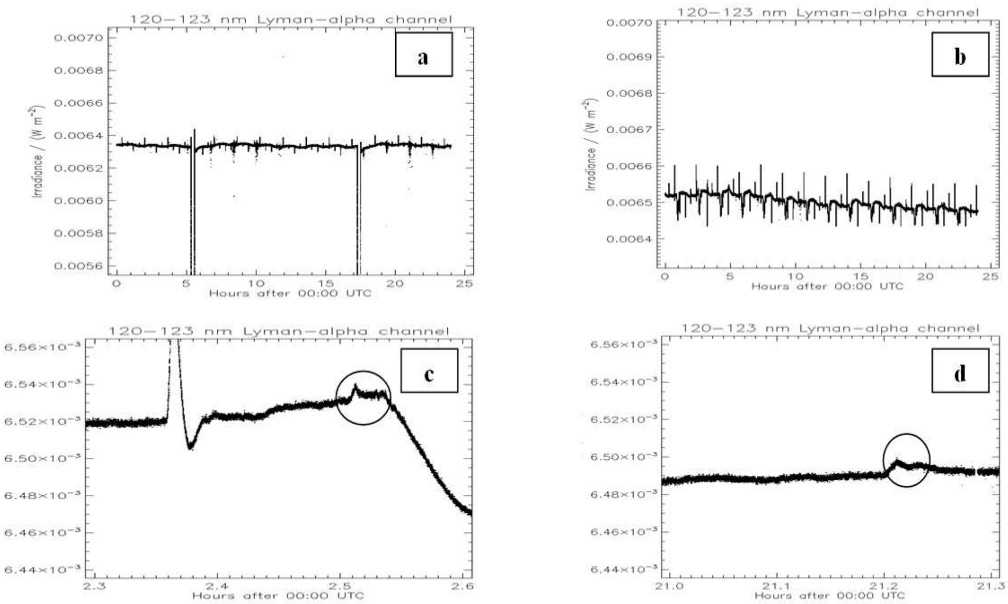

Fig. 2. LYRA Lyman-Alpha data. Top panel Fig. 2a represents a quiet day (February 25, 2010), and Fig. 2b, a disturbed day (February 7, 2010). The bottom panel displays two flare events of M class (Fig. 2c), and C class (Fig. 2d)

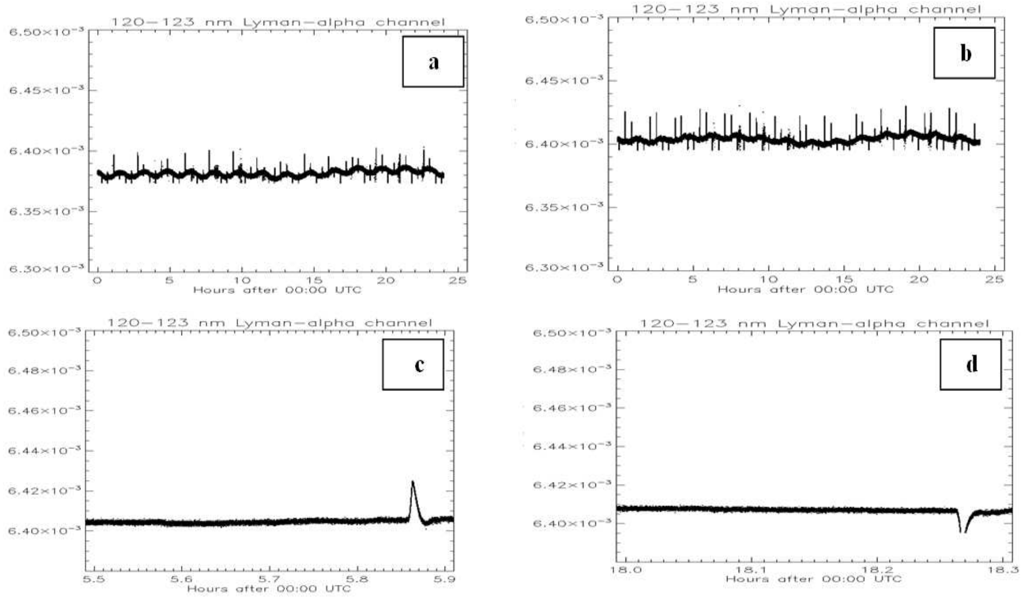

Fig. 3. LYRA Lyman-Alpha data. Fig. 3a (June 1, 2010) represents a quiet day, while Fig. 3b (June 13, 2010) represents a disturbed day. The bottom panels display two flare events of M class (Fig. 3c) and C class (Fig. 3d)

(Fig. 2b). The bottom panel displays two flare events: Fig. 2c, flare event class M 6.4 showing an increase in irradiance, as in Fig. 2d, for a C4.2 flare. The same result appears in November 4, 2010 which has 7 flare events for the disturbed day and November 22, 2010, for the quiet day.

In Fig. 3 we selected a quiet day (June, 1, 2010) and a disturbed day (June 13, 2010 which has 16 flare events). In Fig. 3 the top panel displays both the quiet days (Fig. 3a) and disturbed days (Fig. 3b), and the bottom panel displays two flare events: a class M 1.0 flare event (Fig. 3c), showing that there is no increase in irradiance, and a class B1.8 flare event with no increase as well (Fig. 3d). Also the same result appears in August 7, 2010 which has 4 flare events for the disturbed day and August 24, 2010, for the quiet day.

5. Conclusion. In this paper we want to accurately determine the solar Ly-α irradiance and its evolution through the solar activity cycle 24. We used PROBA-2/LYRA data (level 2) to study the high resolution spectral profiles of Lyman-Alpha irradiance and their variability during the rising phase of solar cycle 24. We compared LYRA with SOLSTICE data and found that there are differences in their behaviour. We found that the SOLSTICE data increase every year on average of 0.052% while average LYRA data dropped each year by 2% from 2010 to 2011, and, then, only by 0.01% from 2012 to 2014 (Table 1).

Although we used level 2 of LYRA data (corrected normally for degradation), the degradation effects are still affecting the data, as evidenced in Fig. 2a. Hence, we cannot follow accurately the long-term variations of the solar irradiance.

We investigated the influence of flares on the flux in the Lyman-Alpha data in 2010, before a too significant degradation of the instrument that can hardly be compensated. There are cases where M class flares do not induce an increase in irradiance while usually they do, and even class C flares in some cases. Lyman-Alpha has certainly an excellent sensitivity to detect flares directly in irradiance that the loss of sensitivity of LYRA/PROBA-2 could not properly quantify. More robust Lyman-Alpha observing experiments are required to properly assess the detection performances. So we do not recommend using Lyman-Alpha channel in LYRA instrument, as the only instrument to investigate the influence of flares on the flux in the Lyman-Alpha data.

As noted at the Introduction accurate hydrogen irradiance emitted by the Sun in the Ly-α line is valuable for estimating the solar energy input that initiates the ionization, chemical and electrical processes in the terrestrial atmosphere, ionosphere and exosphere [1–3]. The situation is similar in the atmospheres and ionospheres of the other planets and their satellites in the solar system [18, 19], and also in cometary atmospheres [9].

The results obtained in the present work will help to improve the solar chromospheric models and provide the input flux in planetary modelling of atmospheric and space weather processes in quiet and disturbed conditions [11, 12, 20–22].

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