A deterministic model for forecasting long-term solar activity

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Eleni Petrakou

APRIM 2017, Talpei

email: helen@petrakou.net

Work performed at the Center for Axion and Precision Physics Research / IBS, S.Korea

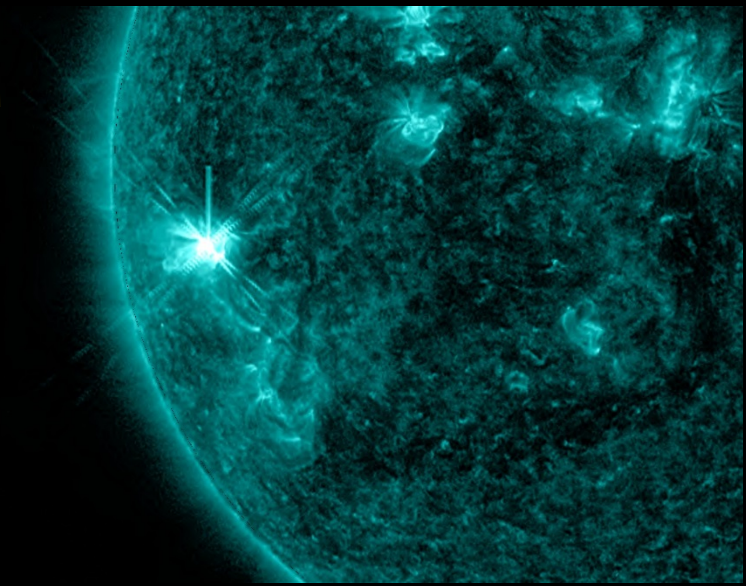

image: Solar Dynamics Observatory (SDO)

Outline

A quantitative model for long-term solar activity is extracted from the data of cycle 21.
Cycles 22-24 are subsequently reproduced and compared to the data.
Further predictions are provided.

Observables: Number of M- and X-class flares.
A main feature is the role of relative ecliptic longitudes of Jupiter and Saturn.

No proposals about physical mechanisms.
Expected to contribute to elucidating the mechanisms and to forecasting of space weather.

astro-ph:1702.00641 (Note: v.2 to be uploaded in ~1 week)

INTRO: INNER PLANETS

astro-ph:1602.03666 investigated whether the timing of solar flares is related to planetary longitudes. The absolute positions of the three inner planets do show noteworthy correlation.

(Analysis related to the CAST experiment =
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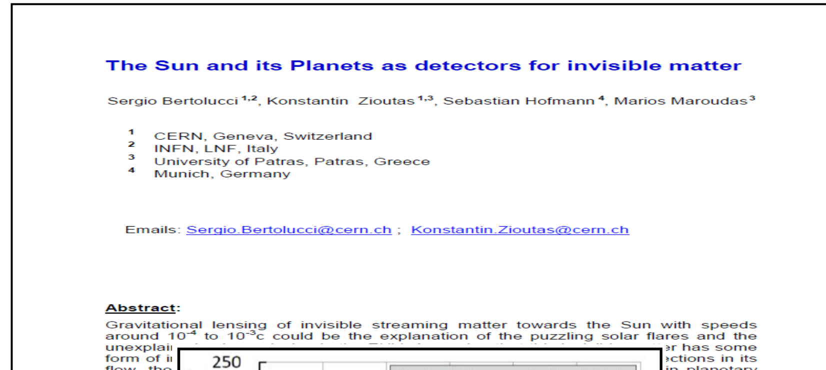
direct dark matter detection.)



The Sun and its Planets as detectors for invisible matter

Sergio Bertolucci [1,2], Konstantin Zioutas [1,3], Sebastian Hofmann [4], Marios Maroudas [3]

1 CERN, Geneva, Switzerland
2 INFN, LNF, Italy
3 University of Patras, Patras, Greece
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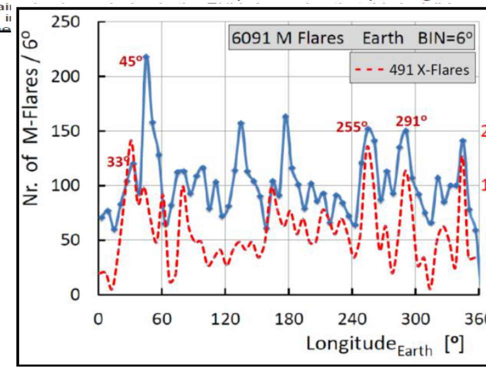

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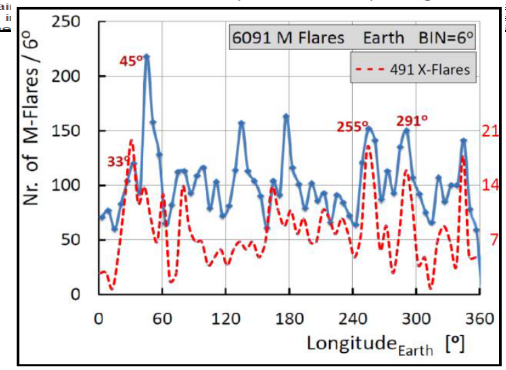
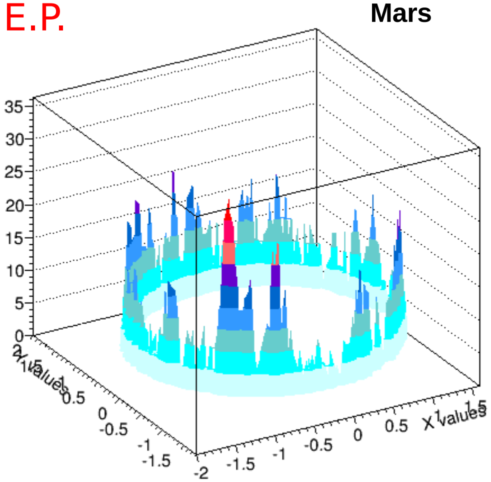


More instances:

E.P.



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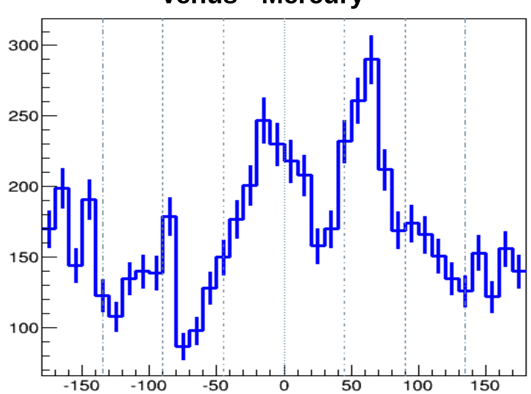


Upon examining the gas giants and considering *relative* positions, a large temporal pattern emerges.

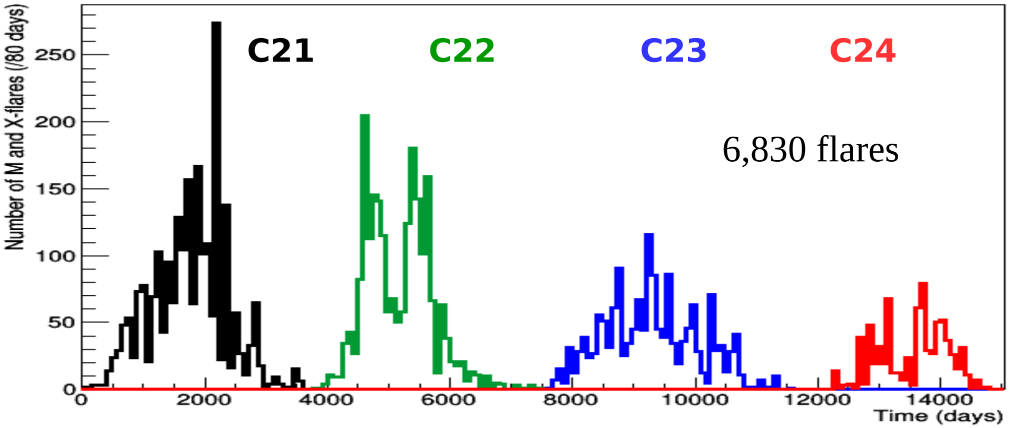
(In the following slides: Only Jupiter and Saturn.)

INTRO: DATA & PRELIMINARY REMARKS

- Number of M- and X-class flares
  - flares used instead of sunspots, being actual events instead of indicators
  - C-flares too affected by randomness
- NOAA SMS and GOES X-ray flux measurements

http://www.swpc.noaa.gov

- Distribution of number of flares vs. time for cycles C21-24, up to end of 2016.
- Binned in 80 days, no other smoothing.
- Definition of cycle start: Appearance of the first M/X flare from a sunspot with reversed magnetic polarity.



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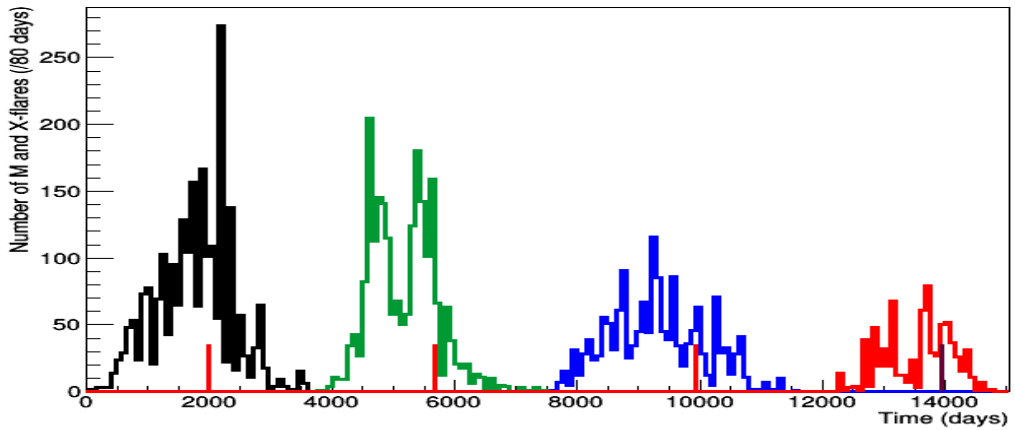

the date for the ongoing C24 is set at the average length (purple line)

Some qualitative observations: temporal middles of cycles (red lines); average of the 24 cycles: 4,015*d*

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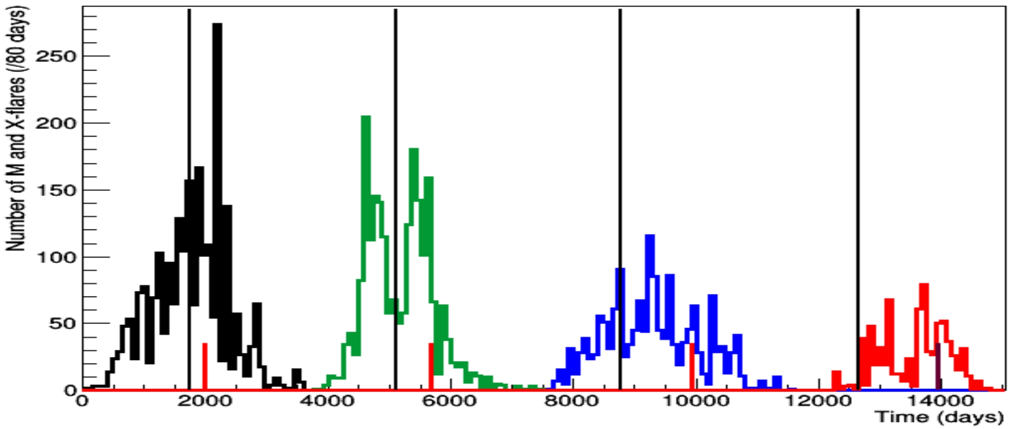

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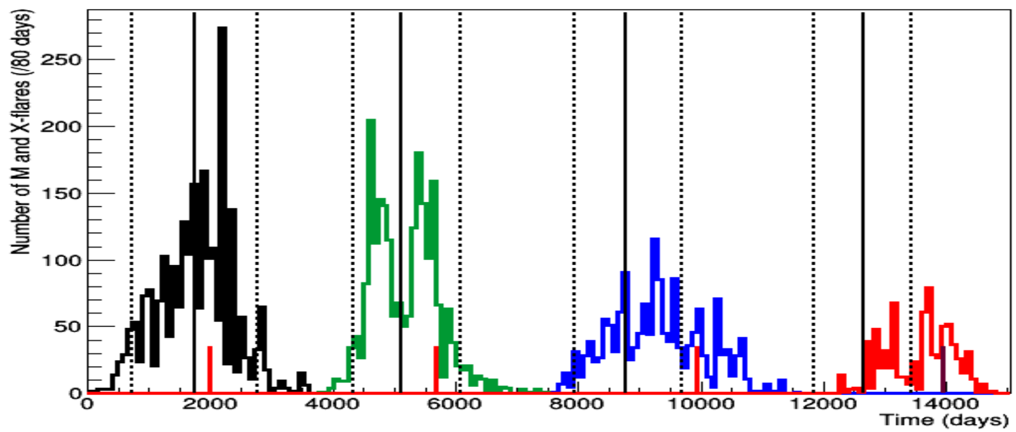

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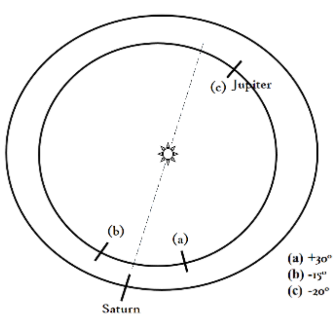
temporal middles of cycles (red lines); average of the 24 cycles: 4,015*d*
dates of Jupiter-Saturn alignments (black lines)
dates of +/-45° around the alignments (dashed lines)

all angles: relative heliocentric ecliptic longitude



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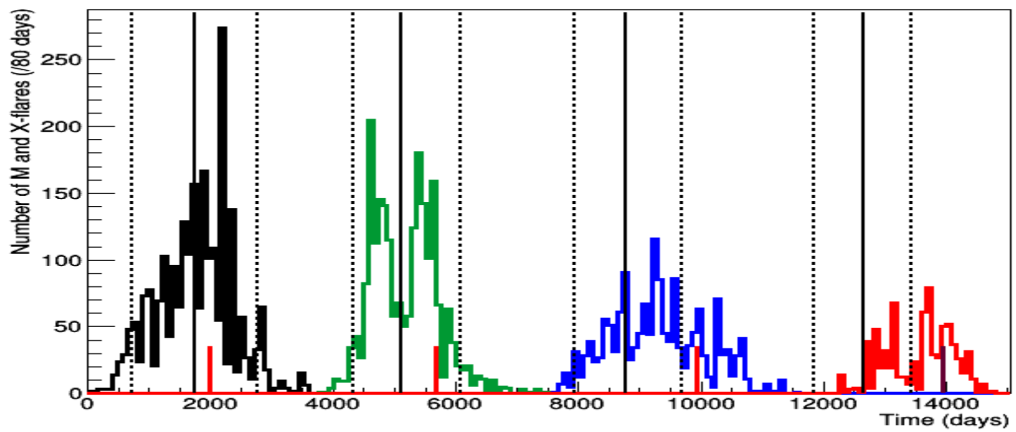

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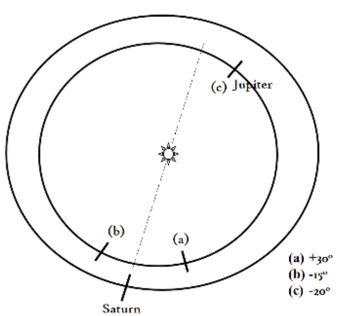


Could we be looking at the coupled effect of two contributions?

EXTRACTION OF THE TWO DISTRIBUTIONS

<u>Proposition</u>: *The main drive behind the evolution of solar activity is strongly correlated to the relative ecliptic longitude of Jupiter and Saturn; however, this effect can only act within the constraints of the "established" 11-year range.*

~ * ~

<u>First step to a model</u>: Obtain the distribution corresponding to each of these two contributions.

Assumptions: - The effect of each contribution to the solar activity follows a Gaussian.

- Both contributions are equally strong(*).

The "established" ~11*y* contribution:
- is centered on the cycles' temporal middles (by default),
- and spans ~11 years (~4,000 days).

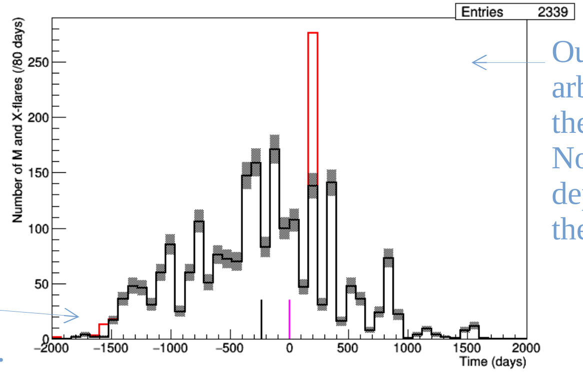
The "J-S" contribution:
- is centered on the dates of their alignments,
- and is stronger mainly in +/-45^0 around them.

These requirements can translate to two Gaussians with defined means and approximately known deviations.

(*) Relaxing this assumption doesn't lead to significantly different results.

EXTRACTION OF THE TWO DISTRIBUTIONS

Assumption: In C21, due to the two planets' conjunction taking place only 238 days before the middle of the cycle, the deployment of both effects *in their full ranges* can be seen.



Outlier; set arbitrarily at half the value.
Note: Strong dependence on the binning start.

Flares of the previous cycle.

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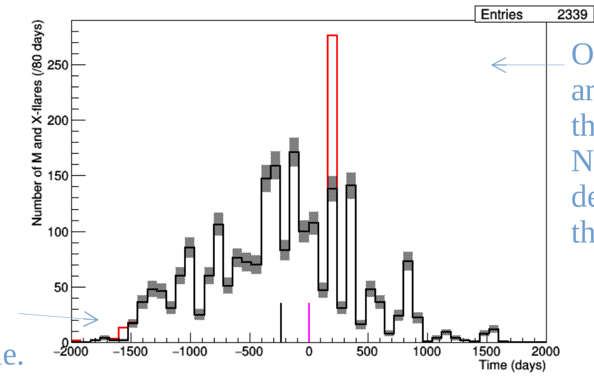

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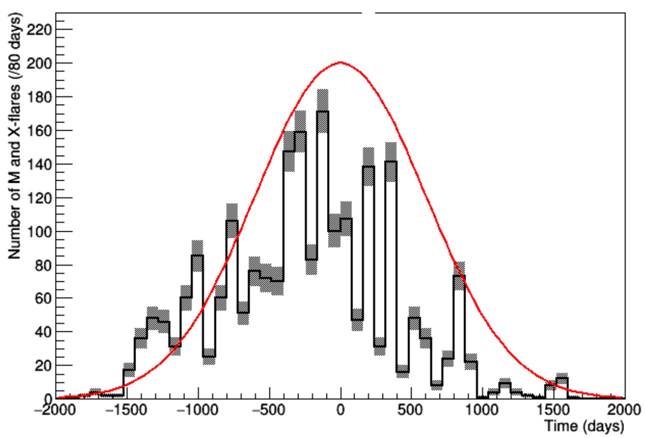
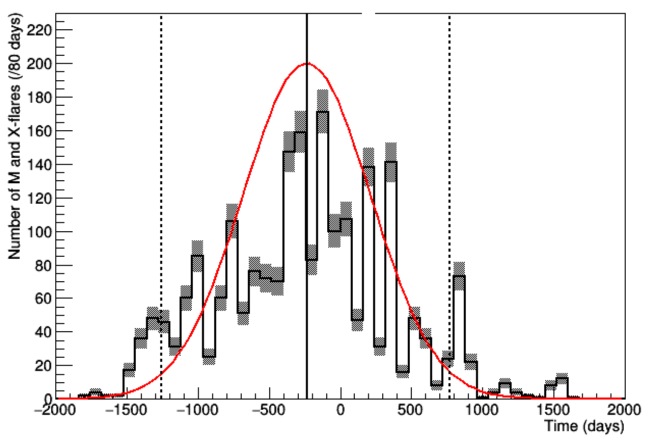
Flares of the previous cycle.

To quantify the contributions, two Gaussians are drawn: One with center on 0 and with 2σ ≈ 3,000*d*, and one centered on -238 days from the middle and with 2σ ≈ range of +/-45°, both with the same constant. The parameters are chosen so that they follow the *envelope* of the data *within each of the two ranges* respectively.



“11-year” Gaussian

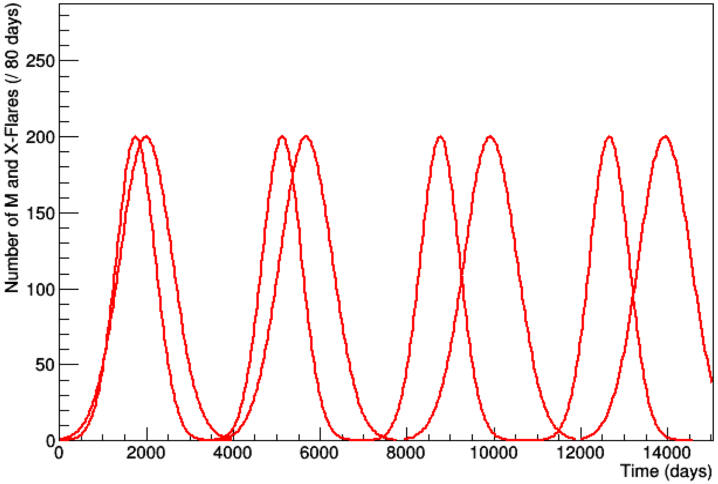


“J-S” Gaussian

COUPLED EFFECT

Second step to a model: Place each distribution on the appropriate date for each cycle: The "11-year" Gaussians are centered on the observed temporal middles, and the "J-S" Gaussians are centered on the two planets' alignments.

Currently, the temporal middle of C24 is placed at 4,015 days after C23's observed middle.



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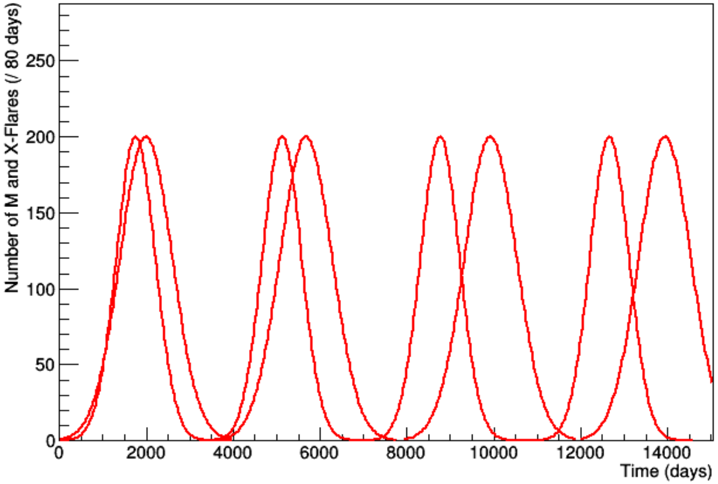
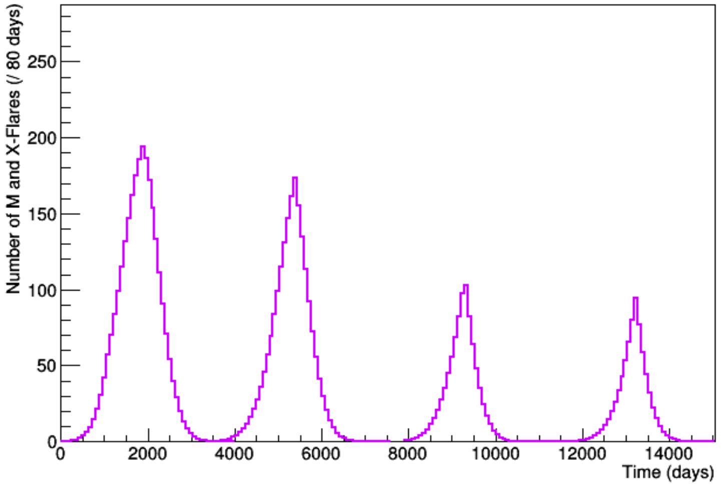
<u>Third step to a model</u>: Obtain the two distributions' overlapping region.

Proposition: This common region describes the combined effect of the two contributions.





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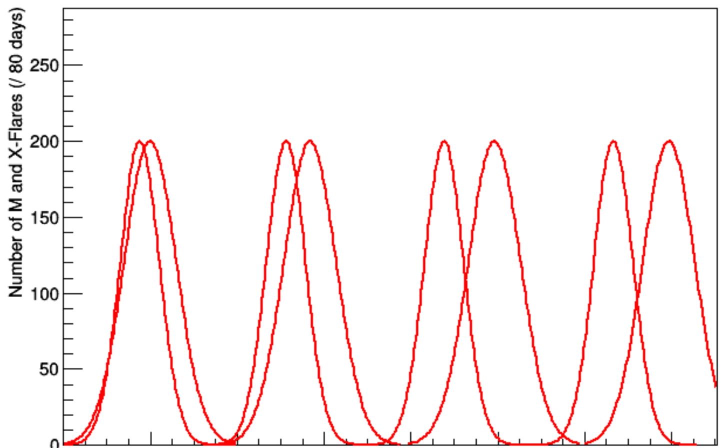
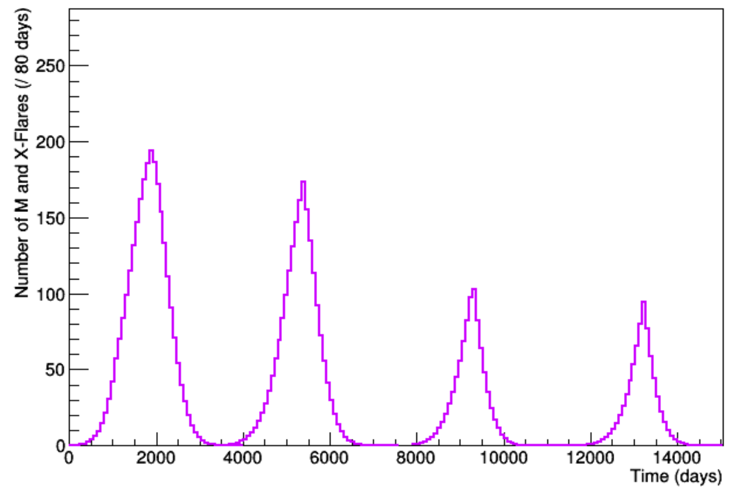
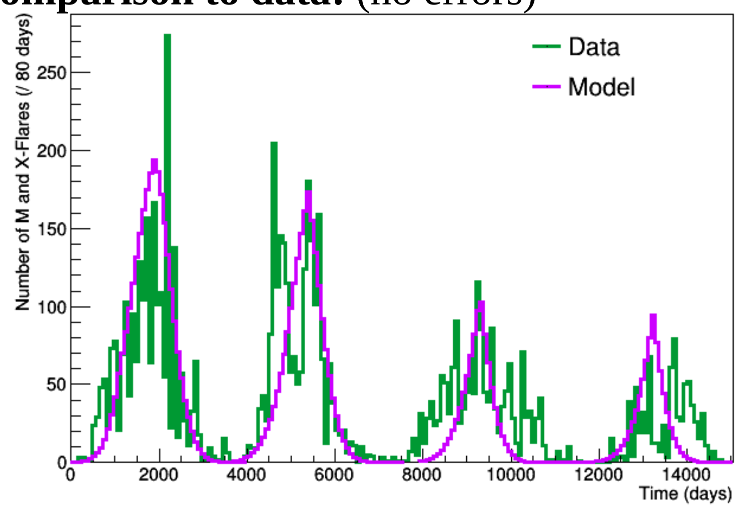




Comparison to data: (no errors)



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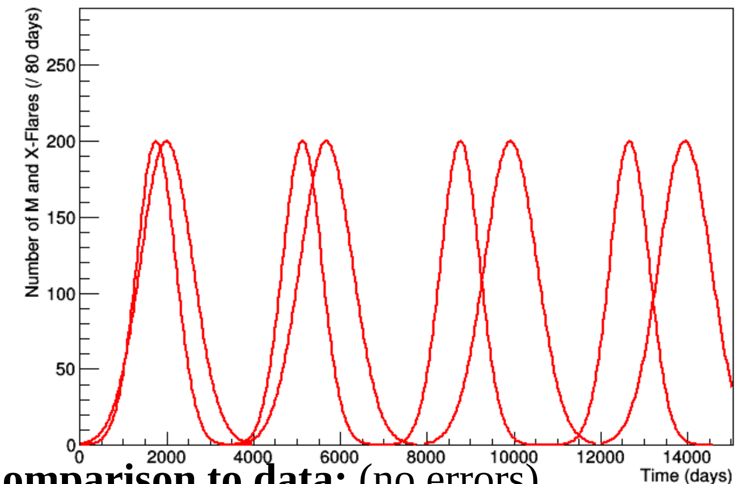

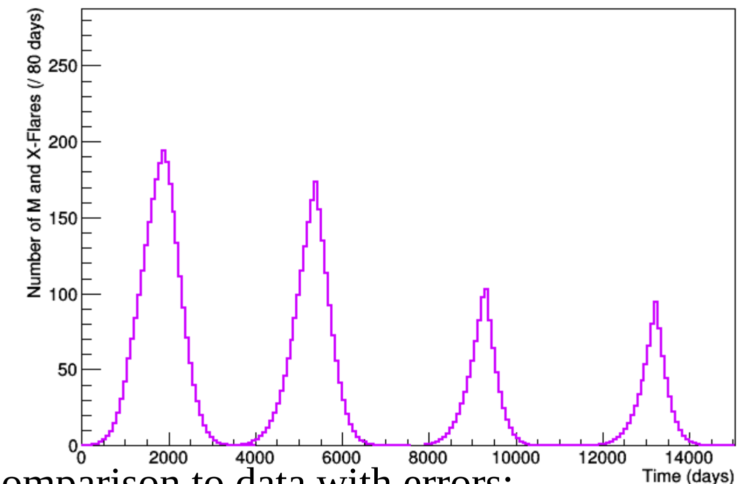

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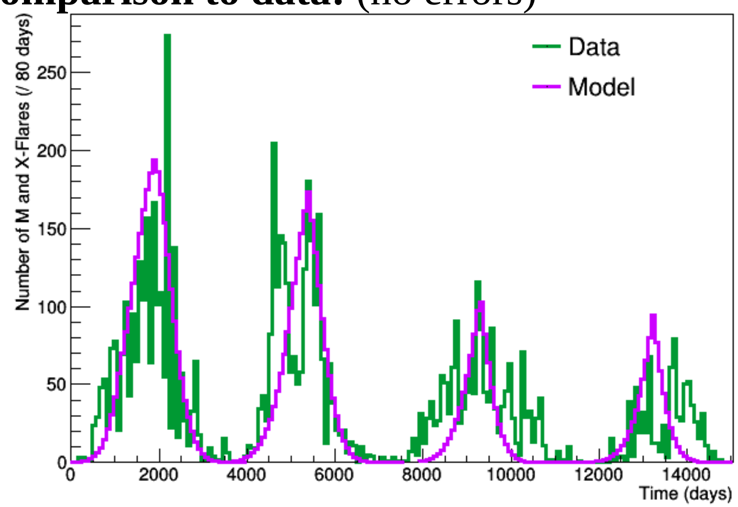
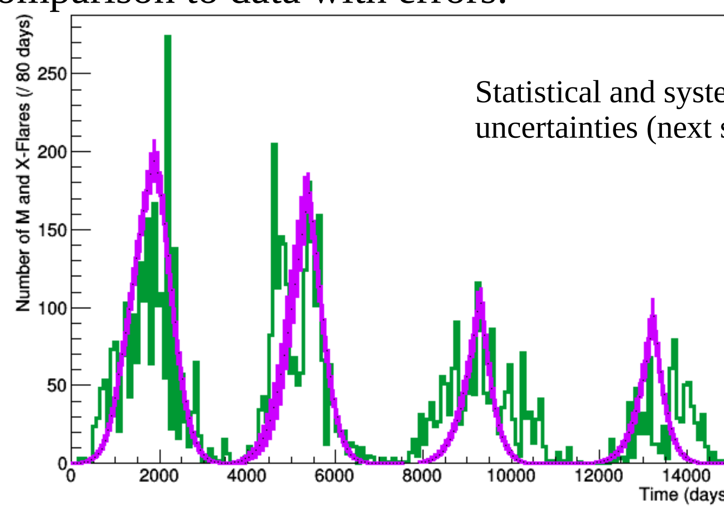


Comparison to data with errors:

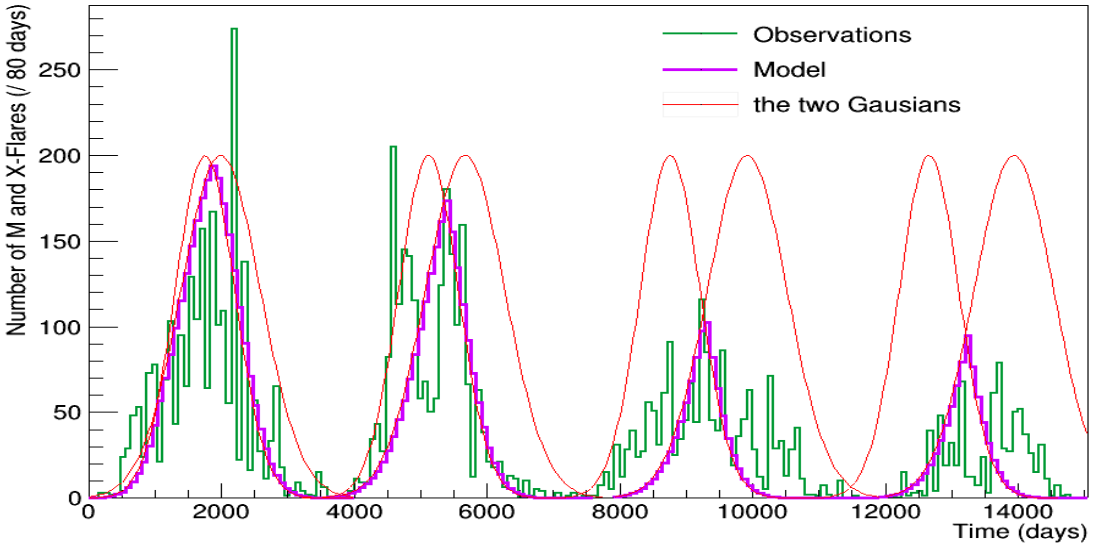


Statistical and systematic uncertainties (next slide)

OVERVIEW OF THE MODEL & STATISTICS

Summary of the process:

- Extract two Gaussians from C21 data, one corresponding to the "11-year modulation" and the other to the "Jupiter-Saturn modulation".
- Time them appropriately in each solar cycle.
- Take their overlapping area.
- Use it to describe the long-term temporal evolution of solar activity.



A note: This scheme implies that as the two planets retreat further than +90°, activity stops. Activity starts building up as they approach anew, within the bounds of the larger modulation.

Statistical tests:

- Correlation between model - data distributions.

  ~0.72/0.87 in all/central ranges, p-value<10^{-7}

- Comparison on indices of main features.
- Kolmogorov-Smirnov on the periodic displacement of the distributions.

Sources of systematic uncertainty:

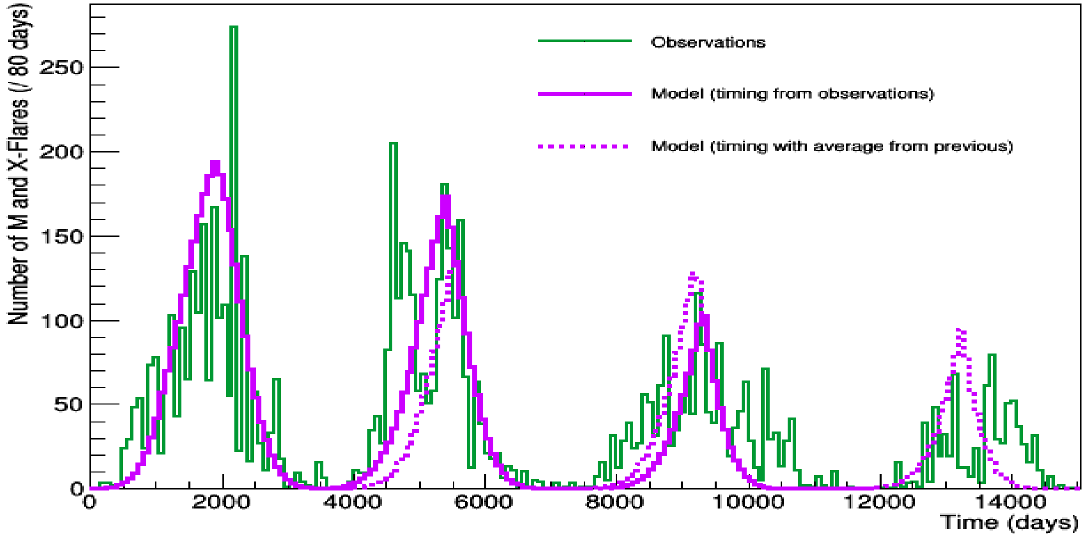
- Binning effects.
- Centering of the "11-year" Gaussian. (next slide)

TIMING OF THE “11-YEAR” GAUSSIAN

So far the model was descriptive but not predictive, since the dates of the cycles’ temporal middles were obtained from the data.

However, in the previous plots the middle of the ongoing C24 was set to 4,015 days after the middle of C23.

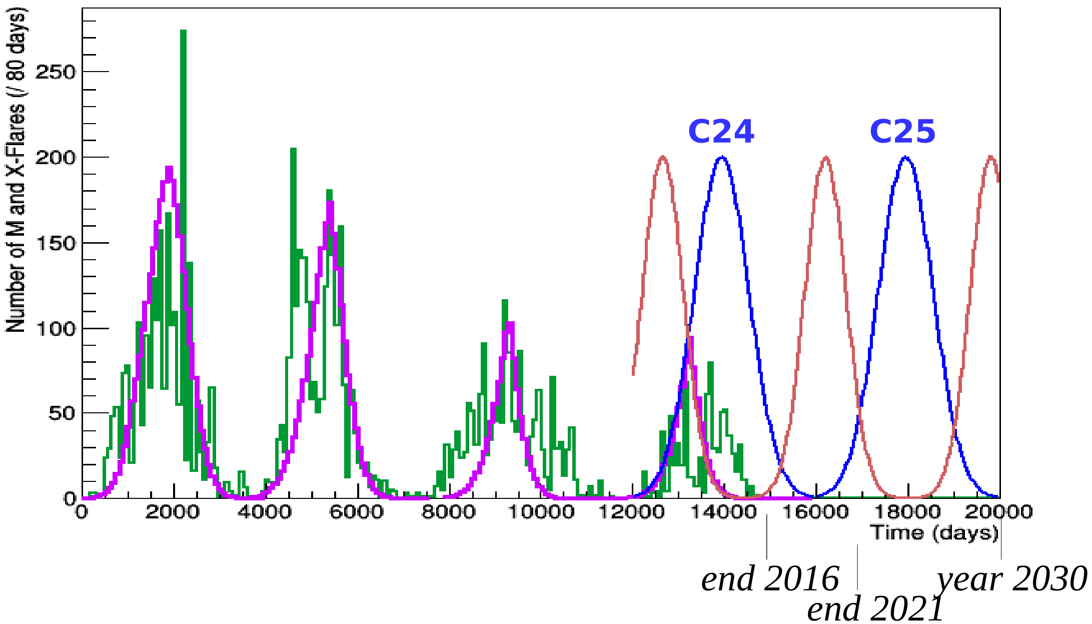
By doing the same for C22 and C23 and comparing with the actual centering of the “11-year” distribution, we can obtain the systematic error associated with the predictive power of the model:



(Note: A possible relation appears between the exact value of the cycles’ duration and the time between the two corresponding successive alignments [to be investigated further].)

FORECASTING

By repeating the centering of the "11-year" Gaussian at 4,015 days, it is possible to provide predictions about the evolution of C25, and the rest of C24:



→Cycle 25: Weaker than C24, dispersed activity.

→ Note: Upon the cycle start, the timing will be known with greater precision (see previous slide).

→Cycle 24: Small resurgence of activity around end 2017/start 2018.

→This results from the empirical observation that the model describes the 0^{o}-45^{o} range, however there is a trend of activity wherever both of the distributions have significant power. This point remains to be quantified.

SUMMARY / A NOTE ON MORE PLANETS

- **A proposed model for the long-term evolution of solar activity, based on a coupling of the relative ecliptic longitude of Jupiter and Saturn and the “11-year” modulation. Results point to a regulation of the solar activity by the approach and retreat of the two gas giants. Quantification by two distributions extracted from the observations of cycle 21 and subsequently timed appropriately.**
- **Main features of cycles 22-24 are reproduced to a good extent. Predictions are provided for cycle 25 (and the rest of 24).**
- **Expected to contribute to the understanding of the underlying mechanisms and forecasting of space weather.**

- astro-ph:1702.00641 [to be updated after APRIM]

➔ Several points for further investigation.

~ * ~

Any dictating physical mechanisms are expected to apply in all cases – possible scenario:

Inner planets: Seem to be correlated to short-term solar activity. [not discussed today]
Jupiter+Saturn: Related to large-scale activity (cycles).
Uranus+Neptune: Possibly very-long-term modulations (conjunctions coinciding with historical extrema).

It can be conceived that solar activity is "bounded” by the internal mechanism (giving the 11-year periodicity), but modulated by the Jupiter-Saturn approach and retreat. Within this long-term modulation, individual solar events are affected by the inner planets’ motion.

A deterministic model for forecasting long-term solar activity
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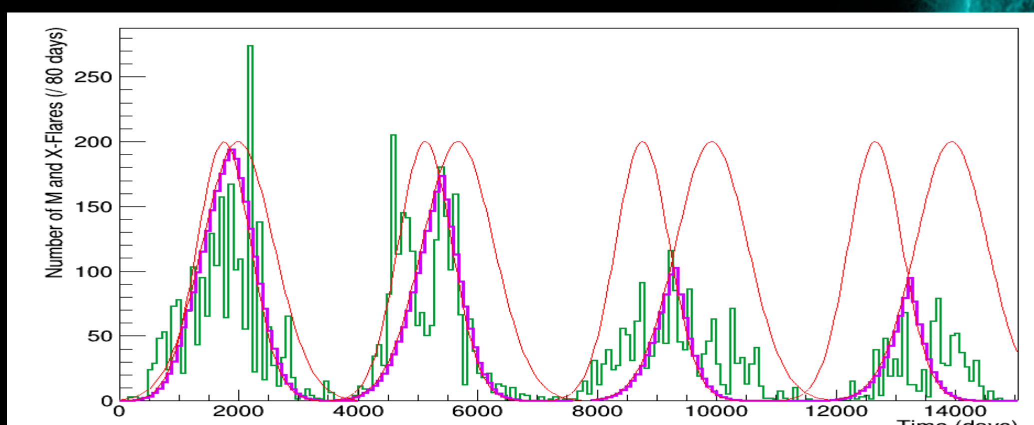
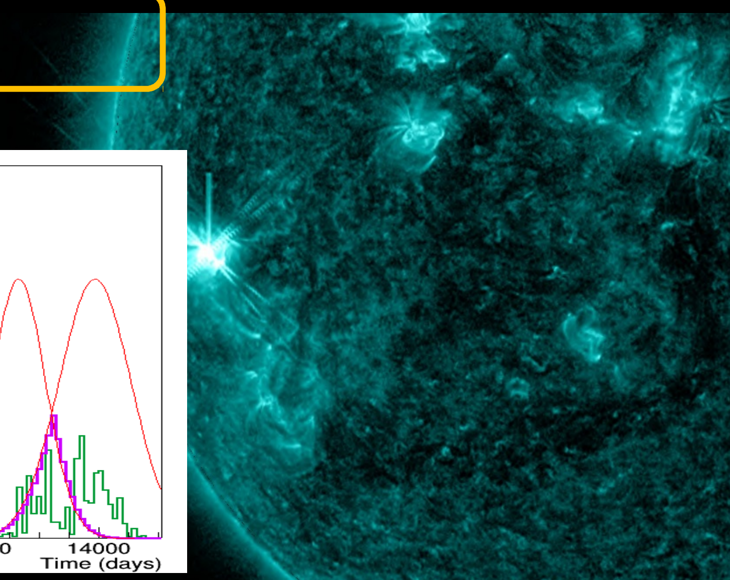
T h a n k   y o u !

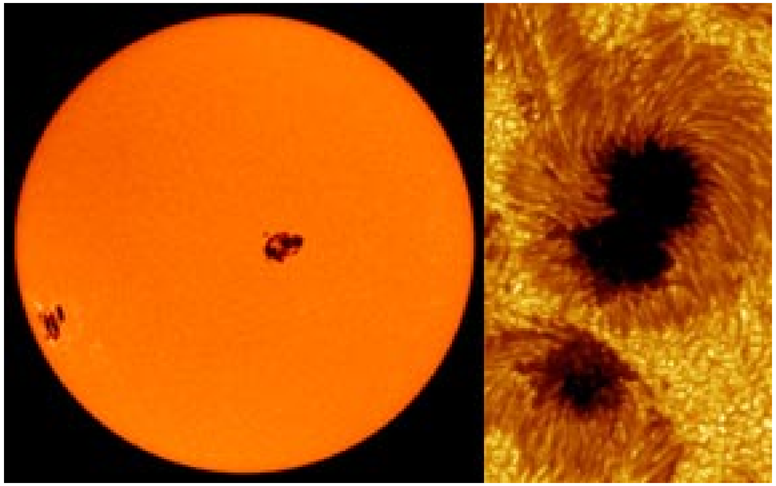




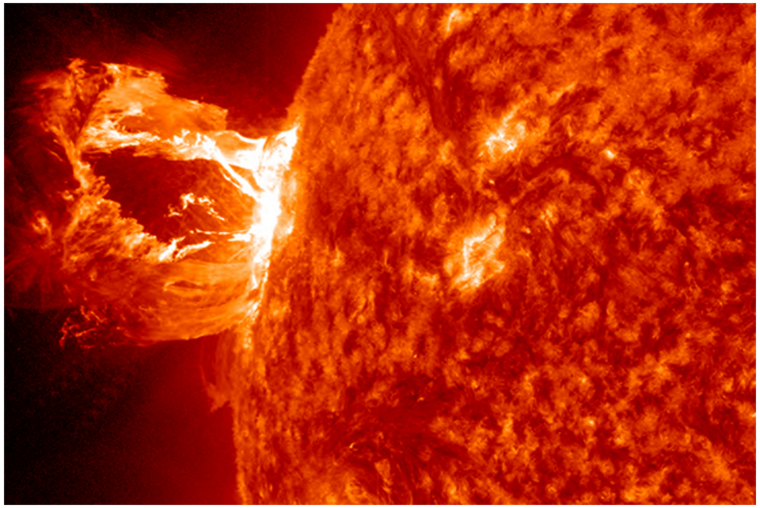
BACK-UP SLIDES

SUNSPOTS & SOLAR FLARES

Sunspots: Darker areas on Sun's surface, corresponding to reduced local temperature, caused by concentrations of magnetic field flux.
Their presence has been recorded for centuries since they belong to the visible spectrum and have a lifetime of several days.



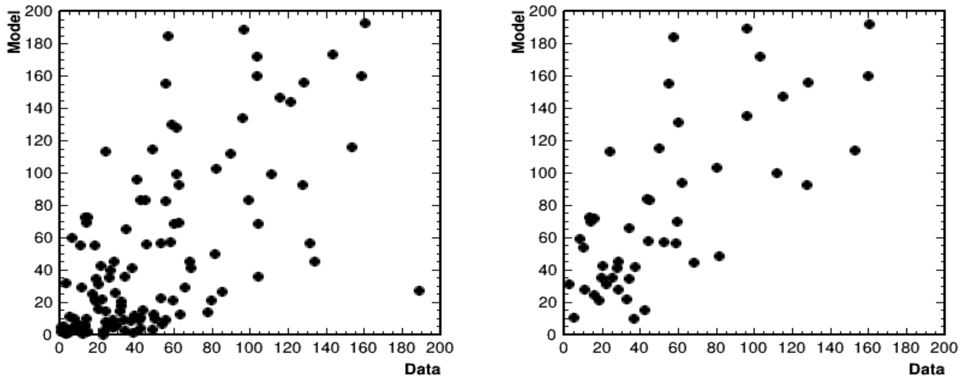
Solar flares: Abrupt release of magnetic energy, spanning the whole electromagnetic spectrum (also including massive particles). Related to sunspots since they both occur in magnetically active regions of the corona.
Their duration is in the order of minutes; their observation was hard before the 1970s.



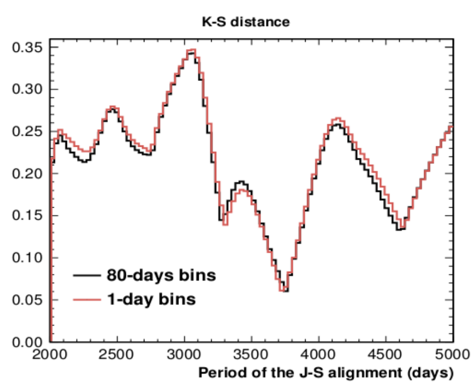
STATISTICAL TESTS

Please note: These plots come from the previous version of the paper (to be updated after APRIM).

Correlation between the distributions of model and data. Left: in the whole range, right: within 0^o-45^o from the alignments.



Kolmogorov-Smirnov for the two Gaussians reproducing the data with random periodic placements. (The “11-year” period was kept constant while varying the average time length between Jupiter-Saturn alignments.) Actual average: 3,634 days.



STATISTICAL TESTS

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Indicators of similarity between model and data.

Table 4: *Values for quantifiers of some of the cycles' main features, both for each cycle and for their RMS. The numbers are the absolute difference between the predictions and the data. Each bin of the two distributions spans 80 days.*

	C 21	**C 22**	**C 23**	**C 24**	**RMS**
Difference in max* in 0º-45º (in counts [and in σs])	33 [1.14]	3 [0.11]	7 [0.41]	2 [0.14]	16.9 [0.61]
Distance between max in 0º-45º (in bins)	0	0	1	2	1.12
Difference in global max (in counts [and in σs])	33 [1.14]	27 [0.99]	7 [0.41]	9 [0.63]	22.1 [0.84]
Distance between start of cycle† (in bins)	3	3	7	3	4.4
Difference in total length of cycle (in days)	n/a	8	8	n/a	-

* "Max" refers to the maximum count. † See text for definition.