# Badania plazmy koronalnej w Zakładzie Fizyki Słońca CBK: Od kamery pin-hole na Verical-1 (1970) do teleskopu STIX na Solar Orbiter (2020)

# Solar Physics Division (SPD) at Wrocław history & present


JANUSZ SYLWESTER

CENTRUM BADAŃ KOSMICZNYCH PAN, ZAKLAD FIZYKI SŁOŃCA

*SPACE RESEARCH CENTRE, POLISH ACADEMY OF SCIENCES*

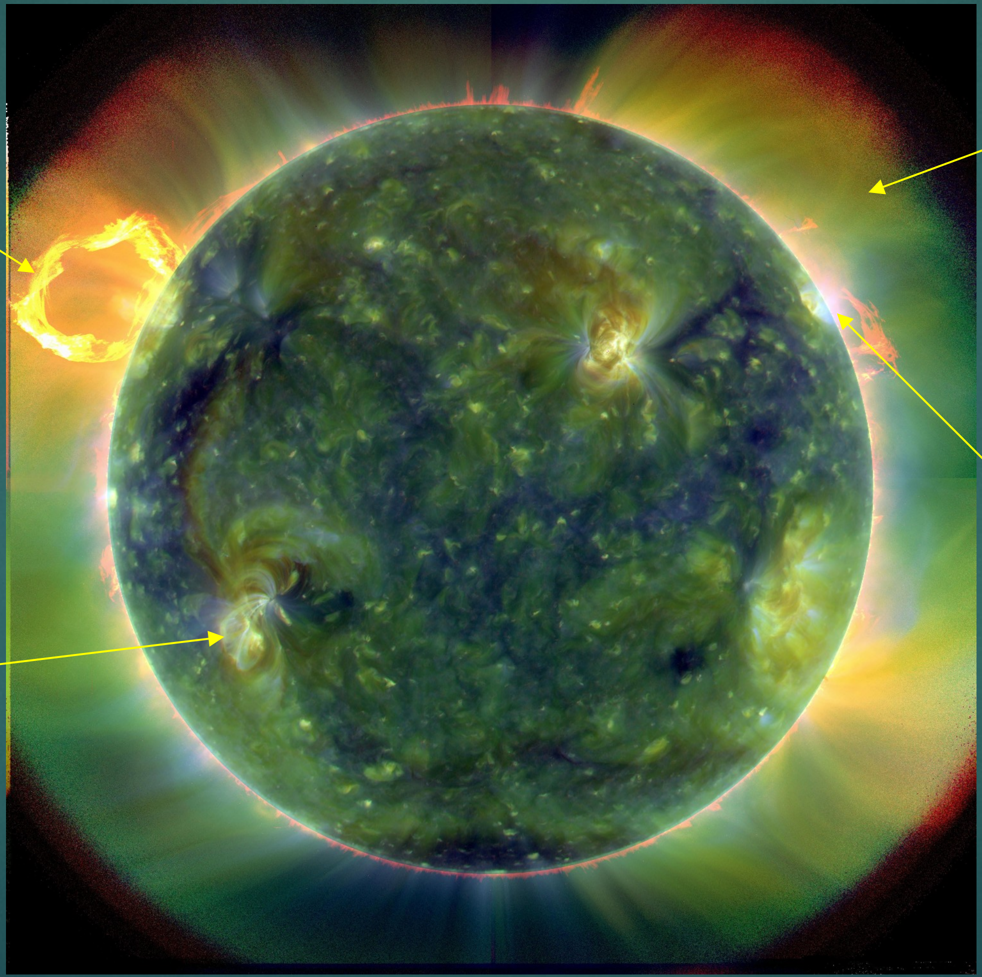
WROCŁAW -- WARSZAWA

# Structures of the solar corona
# NASA Solar Dynamics Observatory: AIA

https://aia.cfa.harvard.edu/images/fulldiskmulticolor.jpg

Protuberances:
T ~ 10 000 K
in optical range

Active regions:
T ~ 2 - 3 MK
EUV & X-rays and
forbidden lines in
optical range



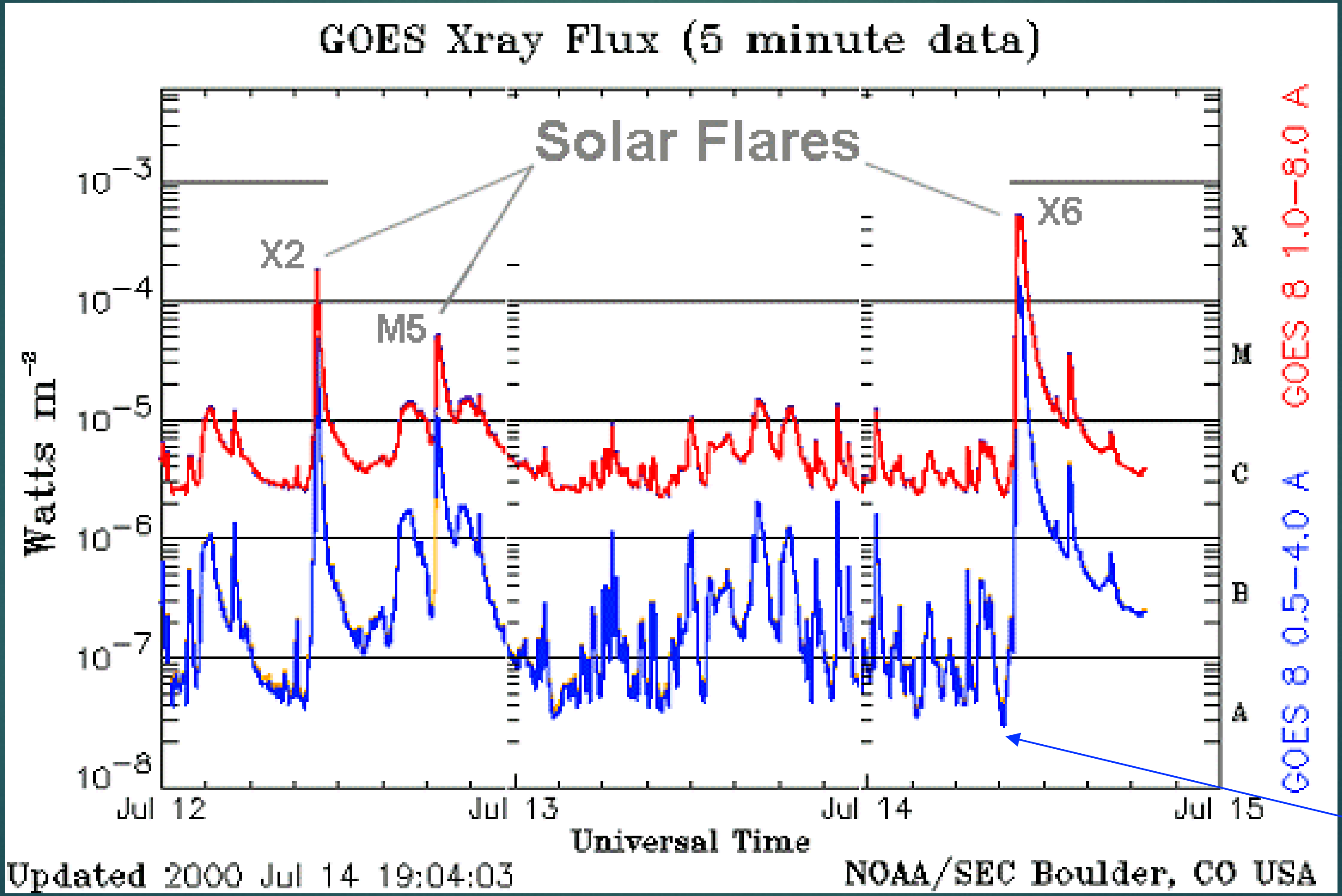
Corona: T ~ 1 MK
EUV & X-rays and
forbidden lines in
optical range

Flares: T ~ 5 -50 MK
Radio, optical EUV
X-rays, □-rays,
non-thermal
emission during the
rise phase

# The Sun is a highly variable star in X-rays



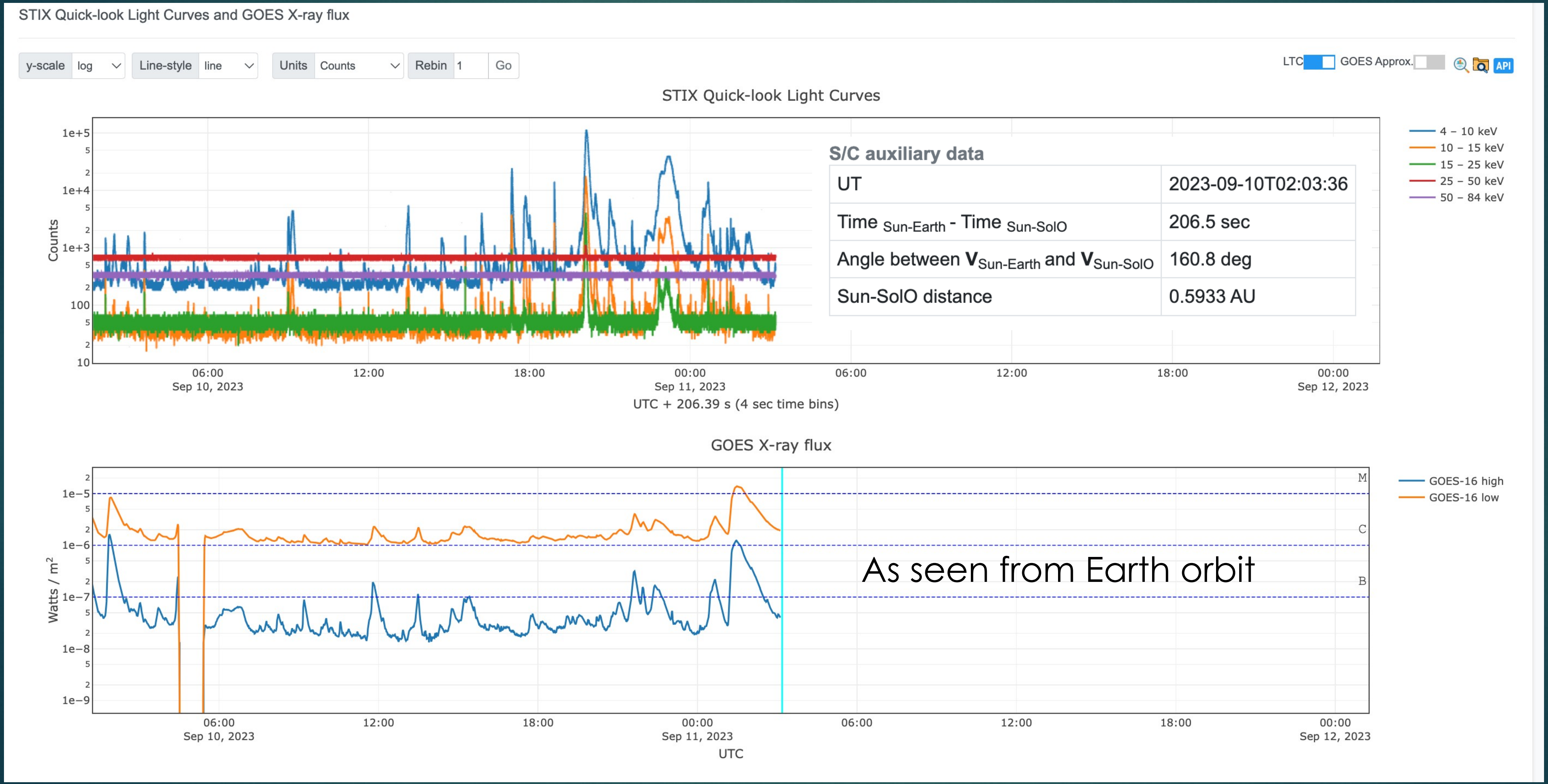
the amplitude reaches 7 – 8 orders of magnitude




The lowest X-ray activity state was not known until SphinX Polish experiment…

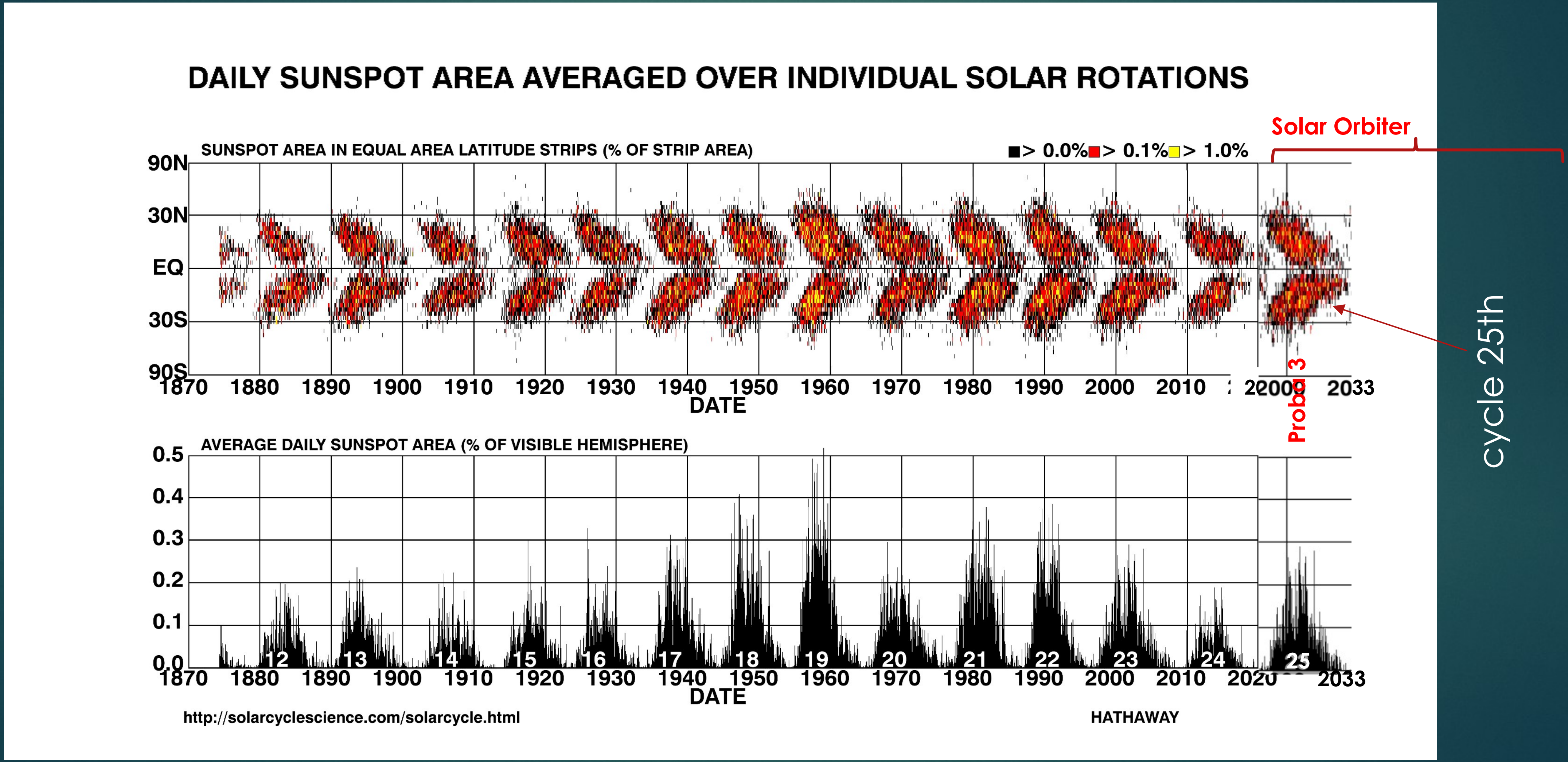
https://spaceweather.com/glossary/flareclasses.html

# Present level of solar activity



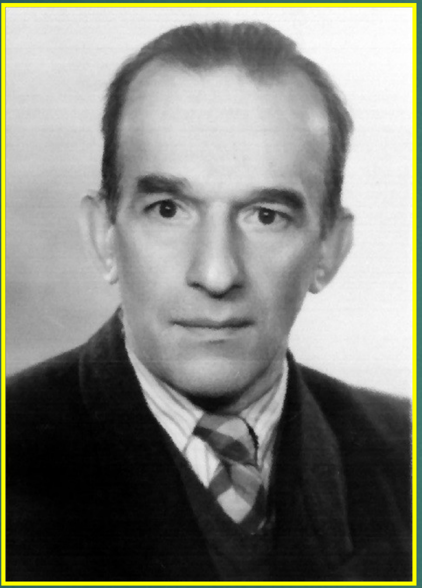
# solar activity in the cycle **25th**





# Founders of the Laboratory

Professors:



Jan Mergentaler
(1901-1995, Lwów-Wroclaw)
in 1951 became interested in Solar Physics – He was the organizer of Wroclaw heliophysics

Stefan Piotrowski (1910–85), supported the development of Wroclaw group remotely, as Head of Astronomical Division, PAS, Warsaw, where our group was initially assigned to.

Jerzy Jakimiec – overlooked from the beginning (early 20 years) the scientific aspects of the program

Antoni Opolski (1913-2014) took charge of the developing Laboratory in 70-ties

Stanislaw Grzedzielski, Zbigniew Klos, Marek Banaszkiewicz and Iwona Stanisławska, as Directors of Space Research Centre, of which the Solar Physics Division is now a part, looked with an interest to the group growth and strength

# Dr. Zbigniew Kordylewski – the constructor

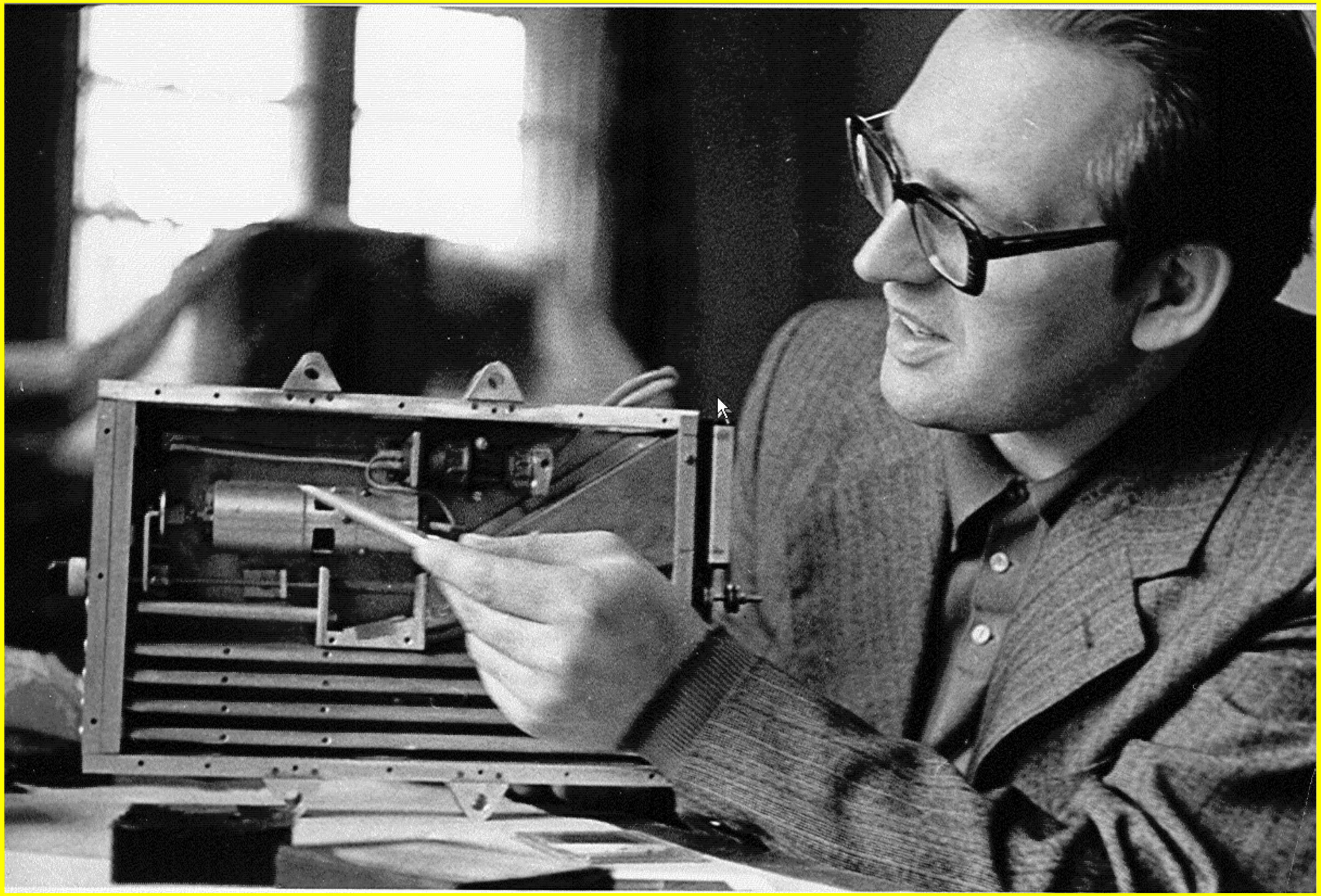


Observations of the X-ray emission of solar active regions on 28 November 1970 and 20 August 1971.

Kordylewski, Z.; Mergentaler, J.; Jakimiec, J.; Sylwester, B.; Sylwester, J.

Space Research XIII, Vol. 2, p. 787 - 792

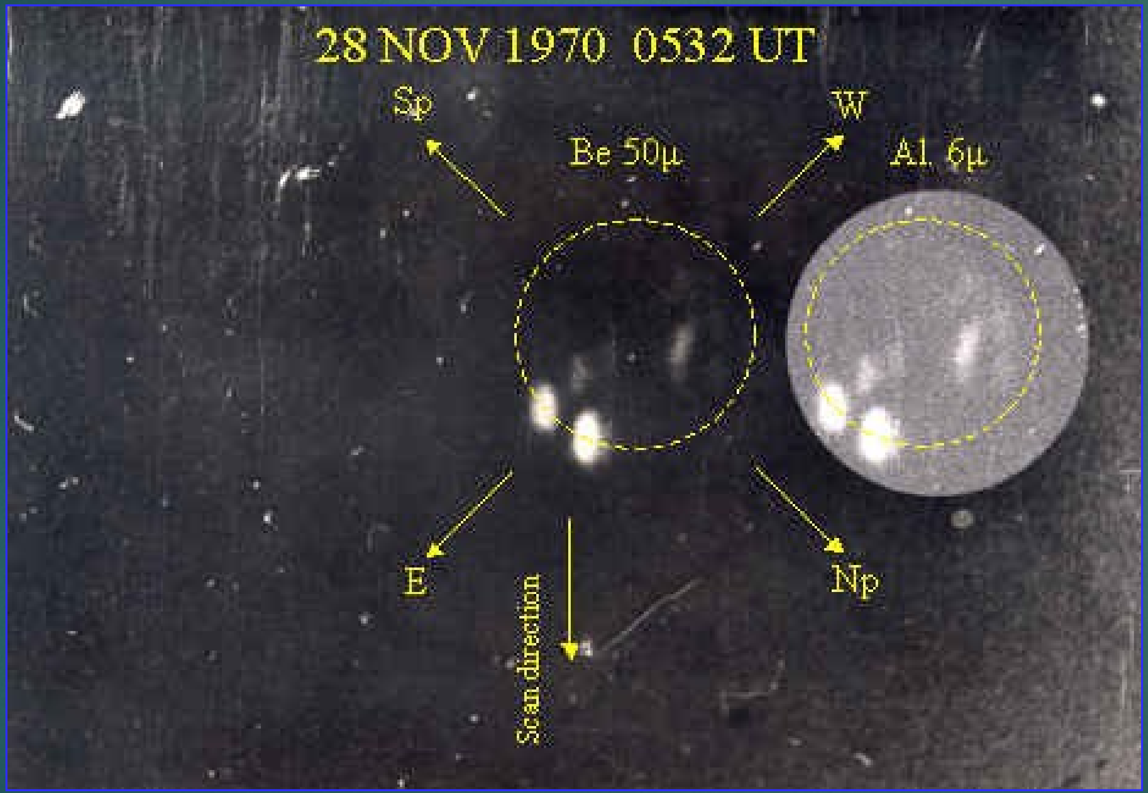
1973



in 1971, presenting Polish part of Vertical-1 payload, after the parachute recovery

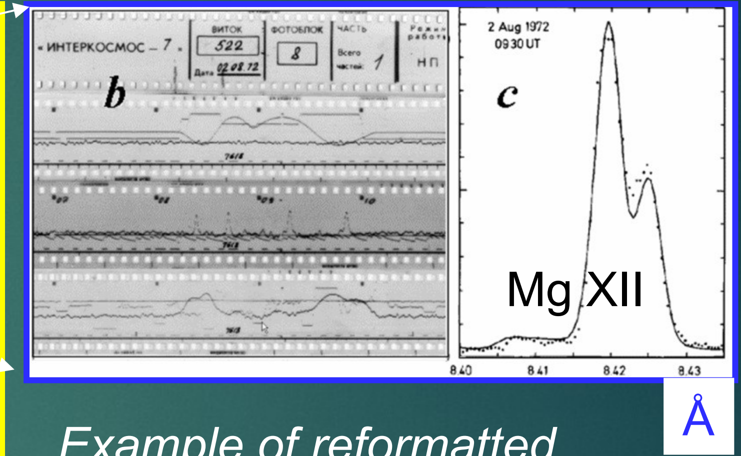
# The first Polish space experiment

**28 November 1970**




The Be 50 μm and Al 6 μm filter images represent emissions from the hotter and cooler plasma. The "filetr ratio" technique allowed to determine the temperature structure within individual active regions. The spatial resolution in the images is rather low (1 arcmin), typical for pin-hole technique

# Solar X-ray spectroscopy


Professor Jakimiec thought us how to handle early observational materials = photographic telemetry records

*Example of reformatted spectrum of the Lyα spin doublet (dotted). The short and long wavelength line components corresponds to transitions in the Mg hydrogen-like ion. The thick line represents best theoretical fit.*

These are still the best resolved spectra in this range

B. Sylwester et al., 1986, Solar Phys. 103, 67

# The people



Barbara Sylwester

Mirek Kowaliński (**head**)

Jarek Bąkała

Stanisław Nowak

Zbigniew Kordylewski

Piotr Podgórski

Jan Merentaler

Daniel Ścisłowski

Jerzy Jakimiec

Anna Kępa

Marek Siarkowski

Witold Trzebiński

# MSSL (Mulard Space Science Lab) – UCL(University Collage London) 1983

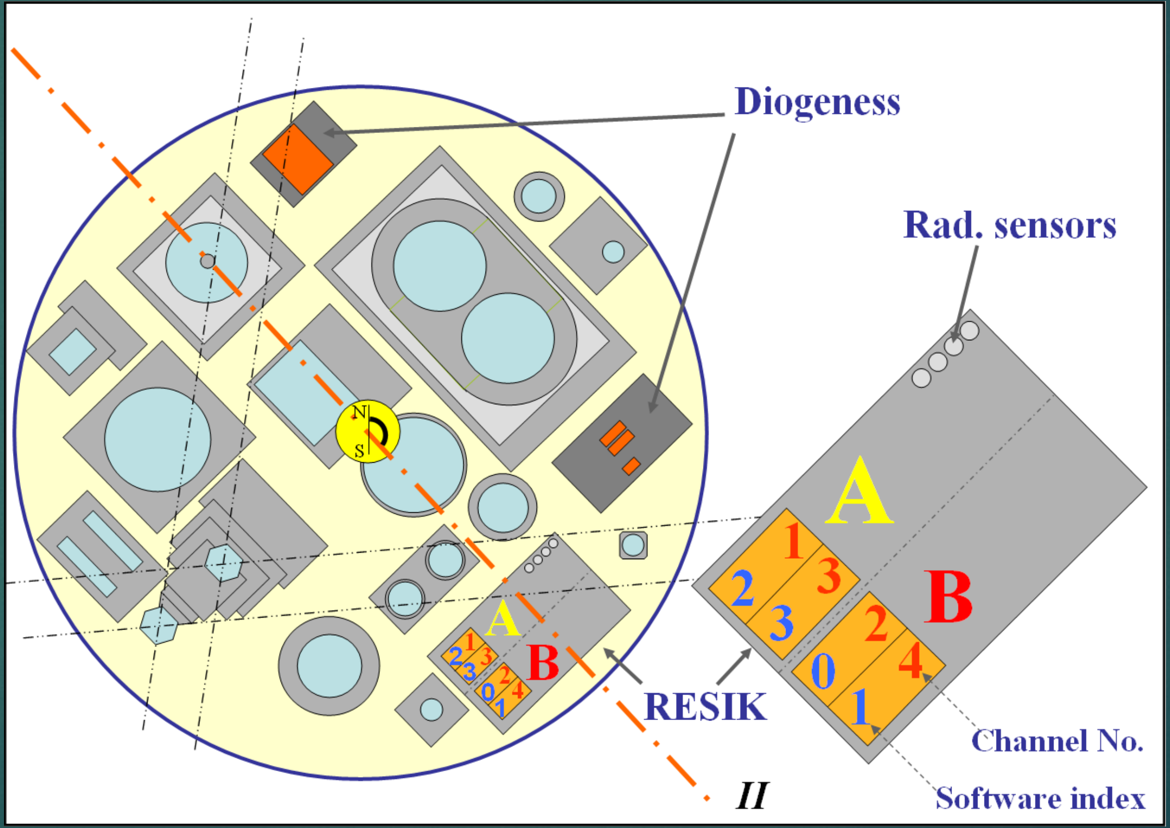

Working on analysis of SMM Ca XIX spectra

# Area of research



- **X-ray spectroscopy**
  - Solar Maximum Mission X-ray Polychromator (Co-I)
  - Yohkoh Bent crystal spectrometer (Co-I)
  - **RESIK** (PI)
  - **SphinX**/ SOXS(Indian) (PI/Co-I)
  - RHESSI
  - **STIX** (3 Co-I)
  - **ASO-S** (Chinese recent mission) (Co-I)
  - Aditya-L1 (Indian mission launched last week - we have Indian post-doc in Wrocław (**Pasific** fellow)
- **Inversion methods in astrophysics**
  - Image reconstructions (SXT-Yohkoh, Trace)
  - Stellar coronae imaging
  - Blind deconvolution (SXT)
  - Bayesian solving of **Fredholm equations**: differential emission measure determinations (SMM, RESIK, Chandrayan-2)
  - Genetic algorithms/**Differential Evolution** (Chandrayan-2) (**ApJL paper after first review**)
- **Instrument construction**
  - INTERBALL-Tail (**RF15-I**)
  - **RESIK** (NRL, RAL, Izmiran)
  - **SphinX** (Chechia)
  - **STIX** (with Switzerland, France, Austria, Germany)

# Our most successful satellite experiments were DIOGENESS & RESIK aboard CORONAS-F 2001 launch




Solar Physics (2005) 226: 45–72

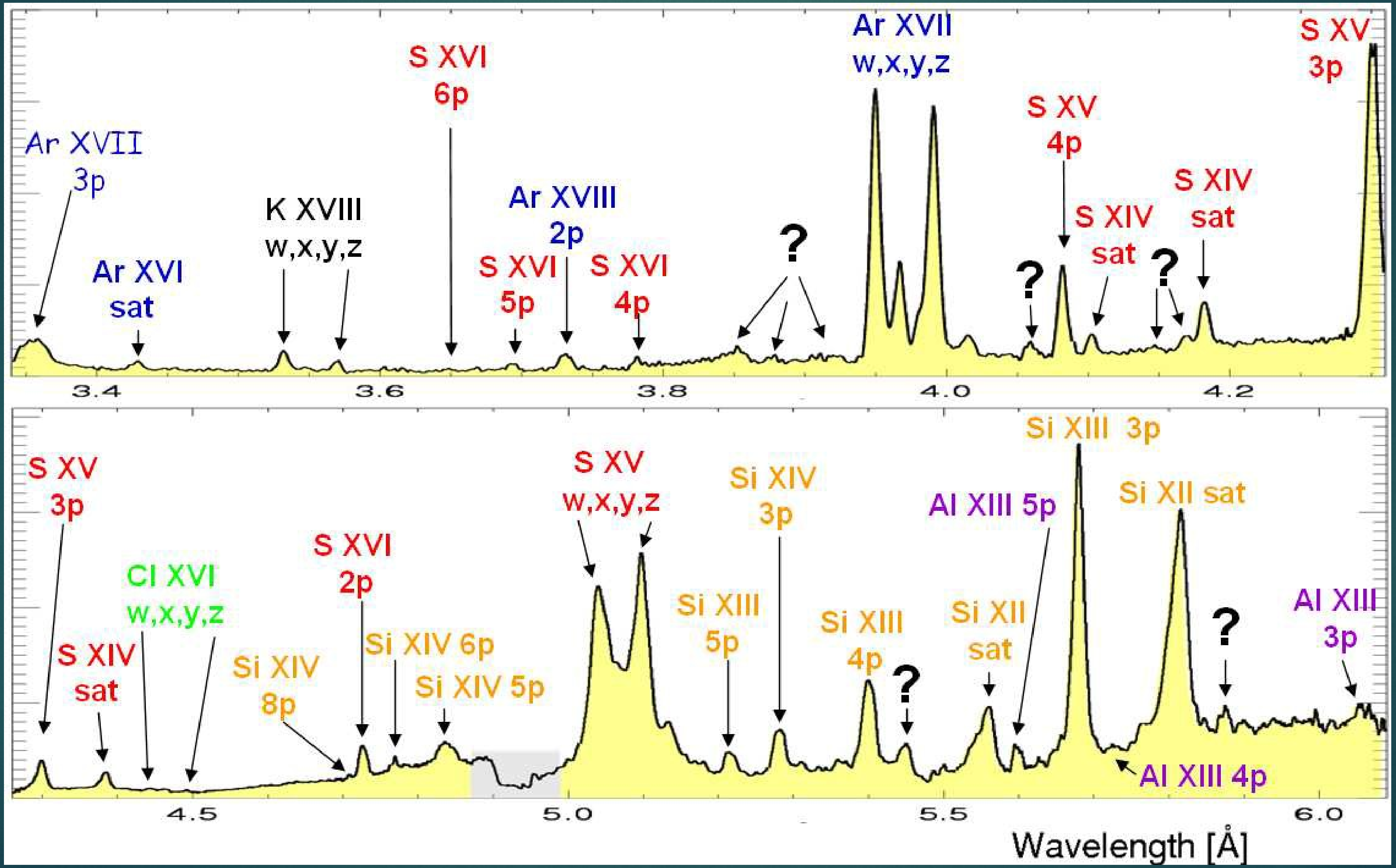

RESIK: A BENT CRYSTAL X-RAY SPECTROMETER FOR STUDIES OF SOLAR CORONAL PLASMA COMPOSITION

J. SYLWESTER[1], I. GAICKI[1], Z. KORDYLEWSKI[1], M. KOWALIŃSKI[1], S. NOWAK[1], S. PŁOCIENIAK[1], M. SIARKOWSKI[1], B. SYLWESTER[1], W. TRZEBIŃSKI[1], J. BĄKAŁA[1], J. L. CULHANE[2], M. WHYNDHAM[2], R. D. BENTLEY[2], P. R. GUTTRIDGE[2], K. J. H. PHILLIPS[3], J. LANG[4], C. M. BROWN[5], G. A. DOSCHEK[5], V. D. KUZNETSOV[6], V. N. ORAEVSKY[6], A. I. STEPANOV[6] and D. V. LISIN[6]

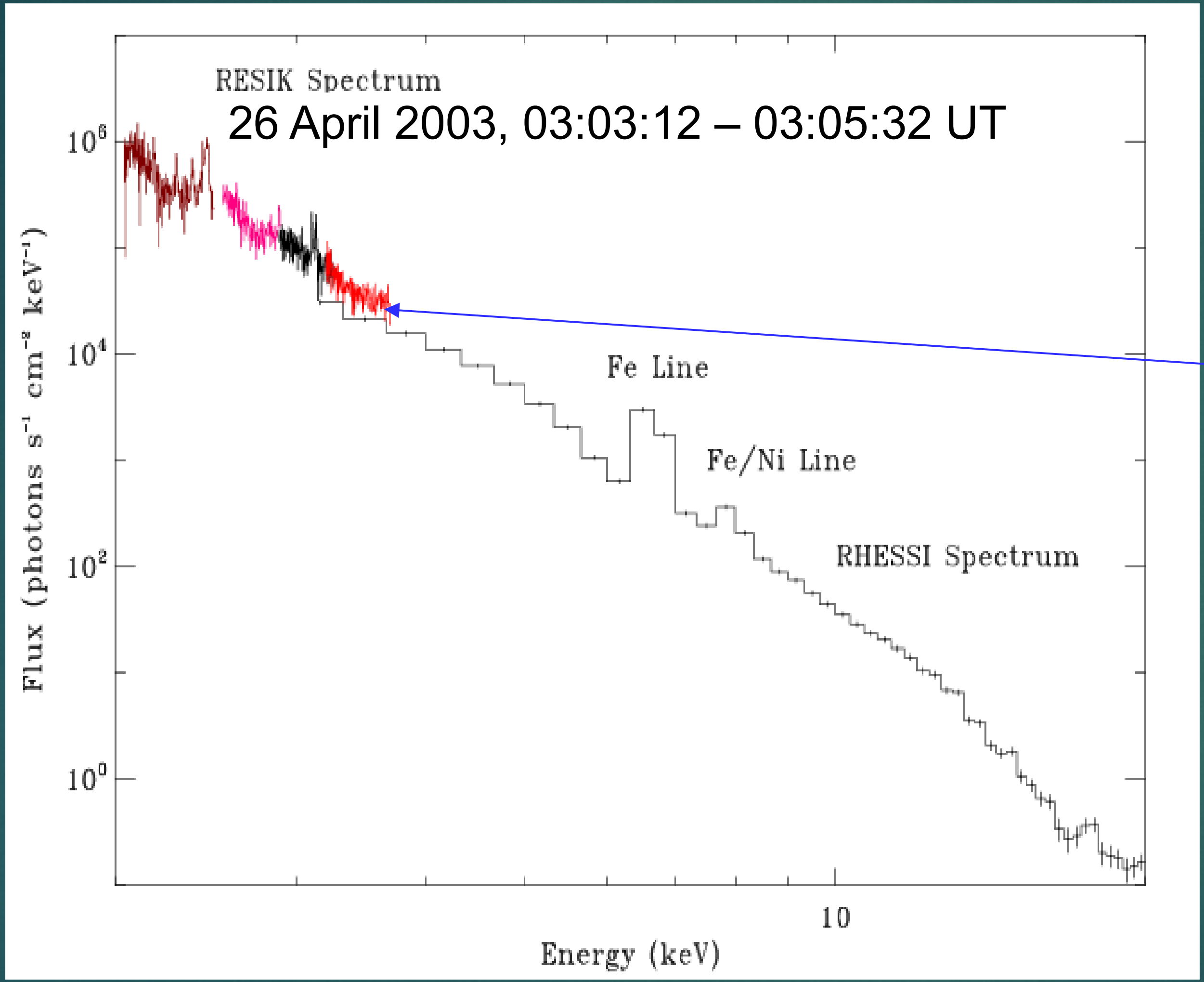
Two Polish spectrometers **RESIK** & **Diogeness** aboard, with dispersion planes aligned; RESIK – BCS like, DIOGENESS – flat crystal, rocking design

# RESIK specta: unique for astrophysics



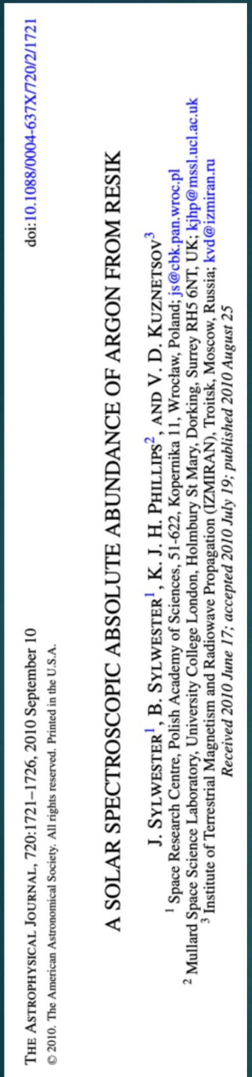


# RESIK & RHESSI




~10% agreement

# Determinations of ABSOLUTE abundances possible


THE ASTROPHYSICAL JOURNAL, 720:1721–1726, 2010 September 10
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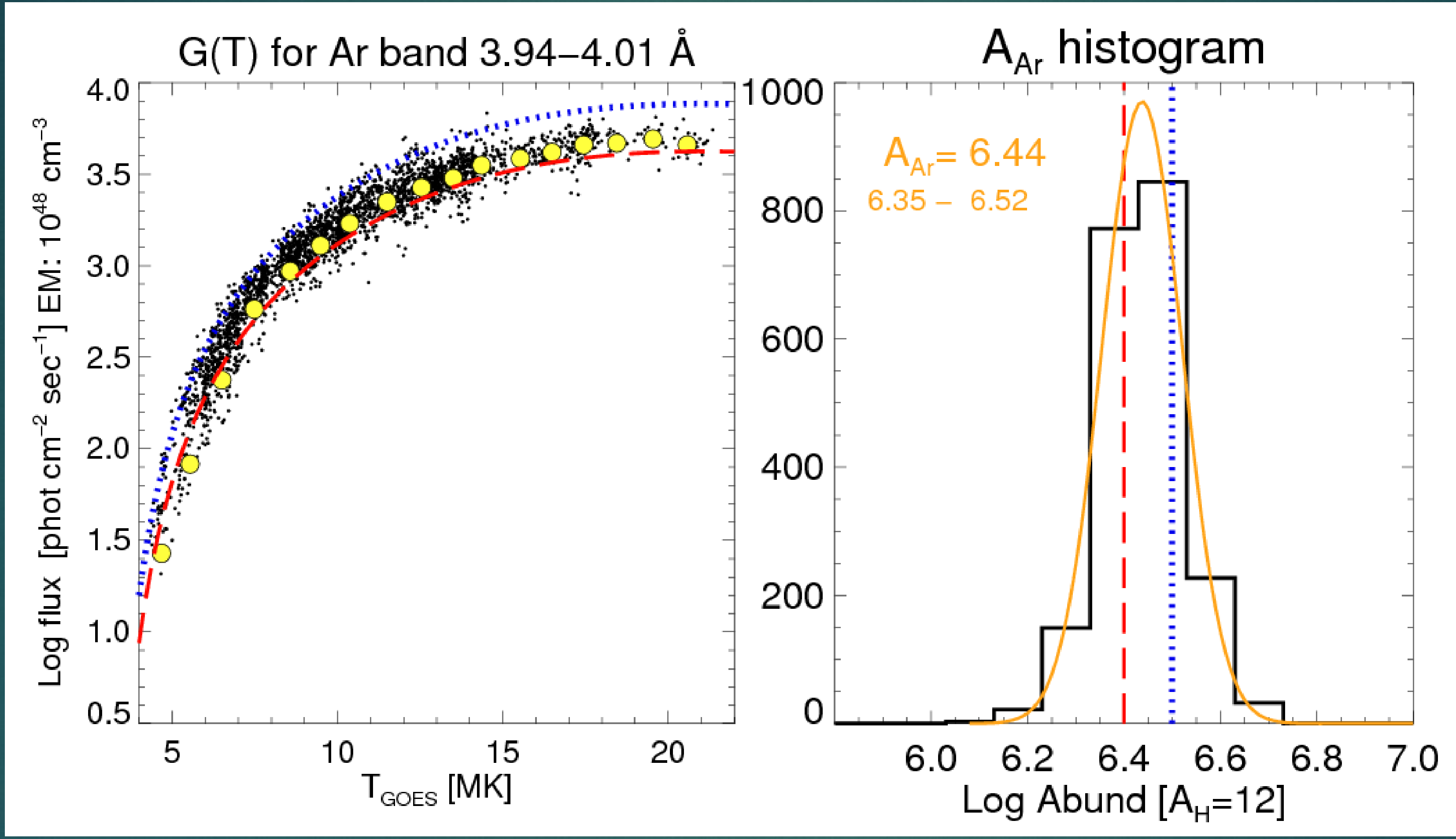
doi:10.1088/0004-637X/720/2/1721

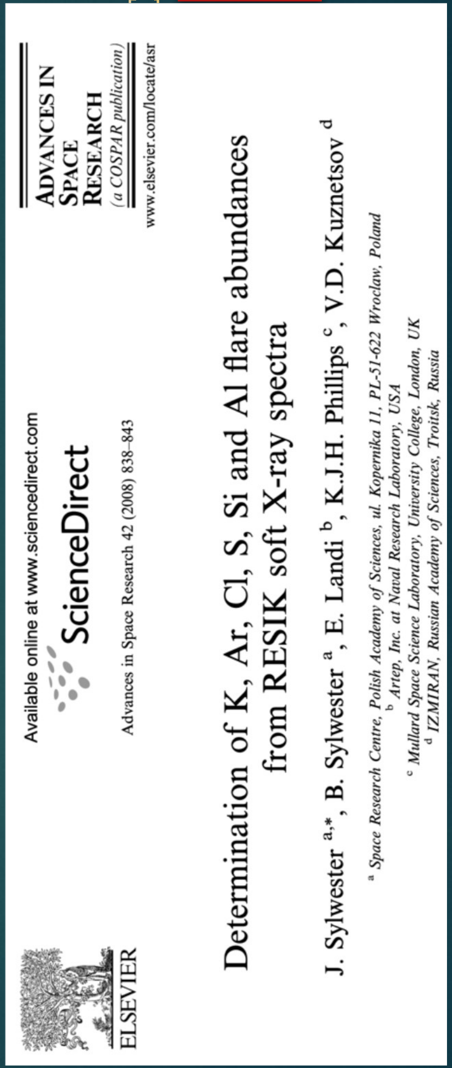
A SOLAR SPECTROSCOPIC ABSOLUTE ABUNDANCE OF ARGON FROM RESIK

J. Sylwester[1], B. Sylwester[1], K. J. H. Phillips[2], and V. D. Kuznetsov[3]

[1] Space Research Centre, Polish Academy of Sciences, 51-622, Kopernika 11, Wrocław, Poland; js@cbk.pan.wroc.pl
[2] Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK; kjhp@mssl.ucl.ac.uk
[3] Institute of Terrestrial Magnetism and Radiowave Propagation (IZMIRAN), Troitsk, Moscow, Russia; kvd@izmiran.ru

Received 2010 June 17; accepted 2010 July 19; published 2010 August 25





Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 42 (2008) 838–843
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr
ELSEVIER

Determination of K, Ar, Cl, S, Si and Al flare abundances from RESIK soft X-ray spectra

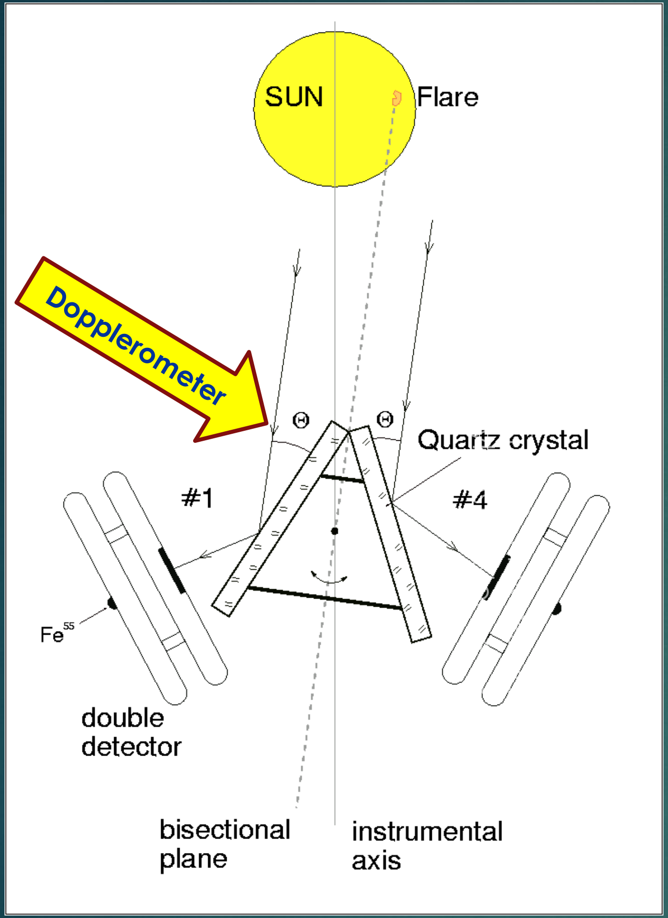
J. Sylwester [a,*], B. Sylwester [a], E. Landi [b], K.J.H. Phillips [c], V.D. Kuznetsov [d]

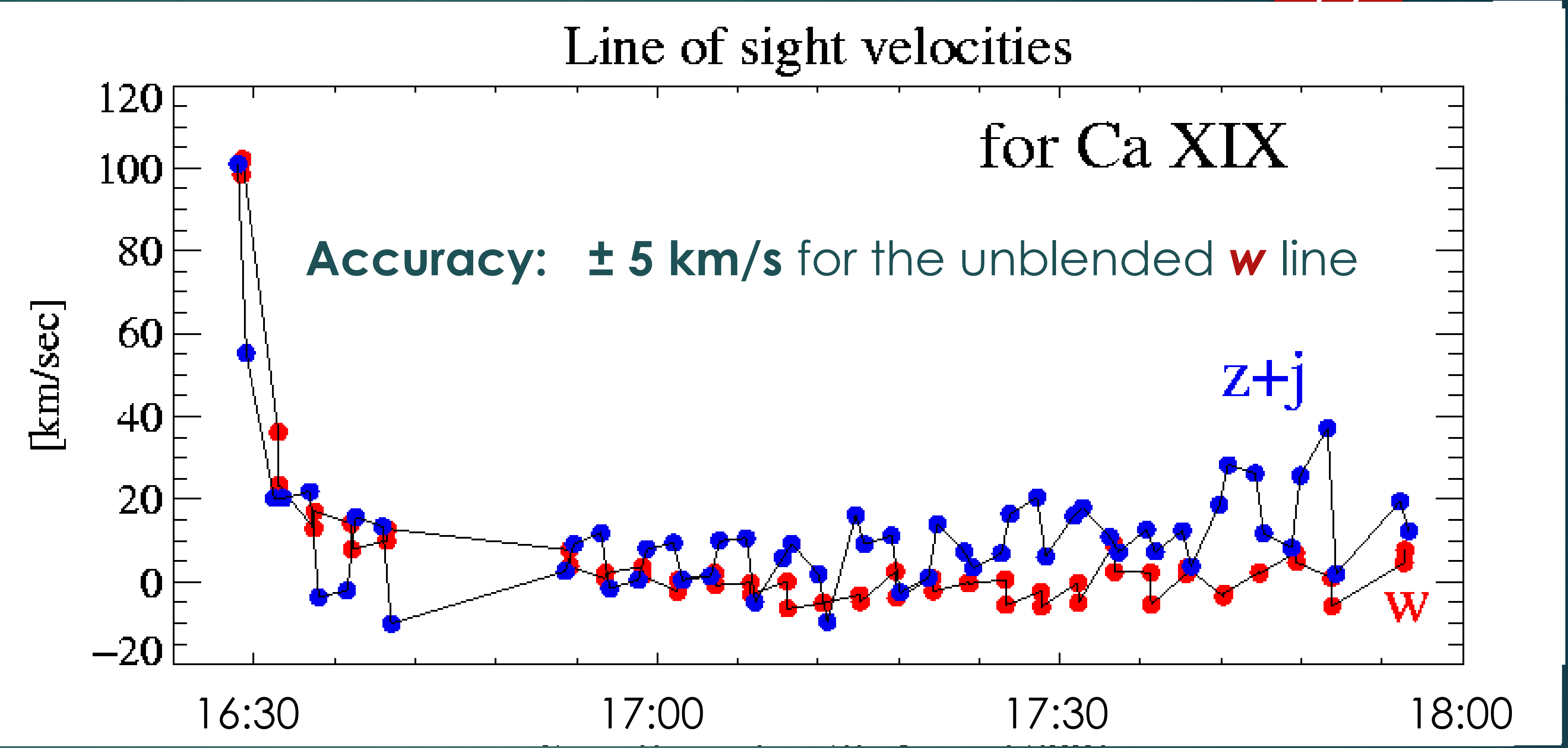
[a] Space Research Centre, Polish Academy of Sciences, ul. Kopernika 11, PL-51-622 Wrocław, Poland
[b] Artep, Inc. at Naval Research Laboratory, USA
[c] Mullard Space Science Laboratory, University College, London, UK
[d] IZMIRAN, Russian Academy of Sciences, Troitsk, Russia

This is the FIRST spectroscopic determination of solar elemental abundance for **argon**

# X-ray Dopplerometer results

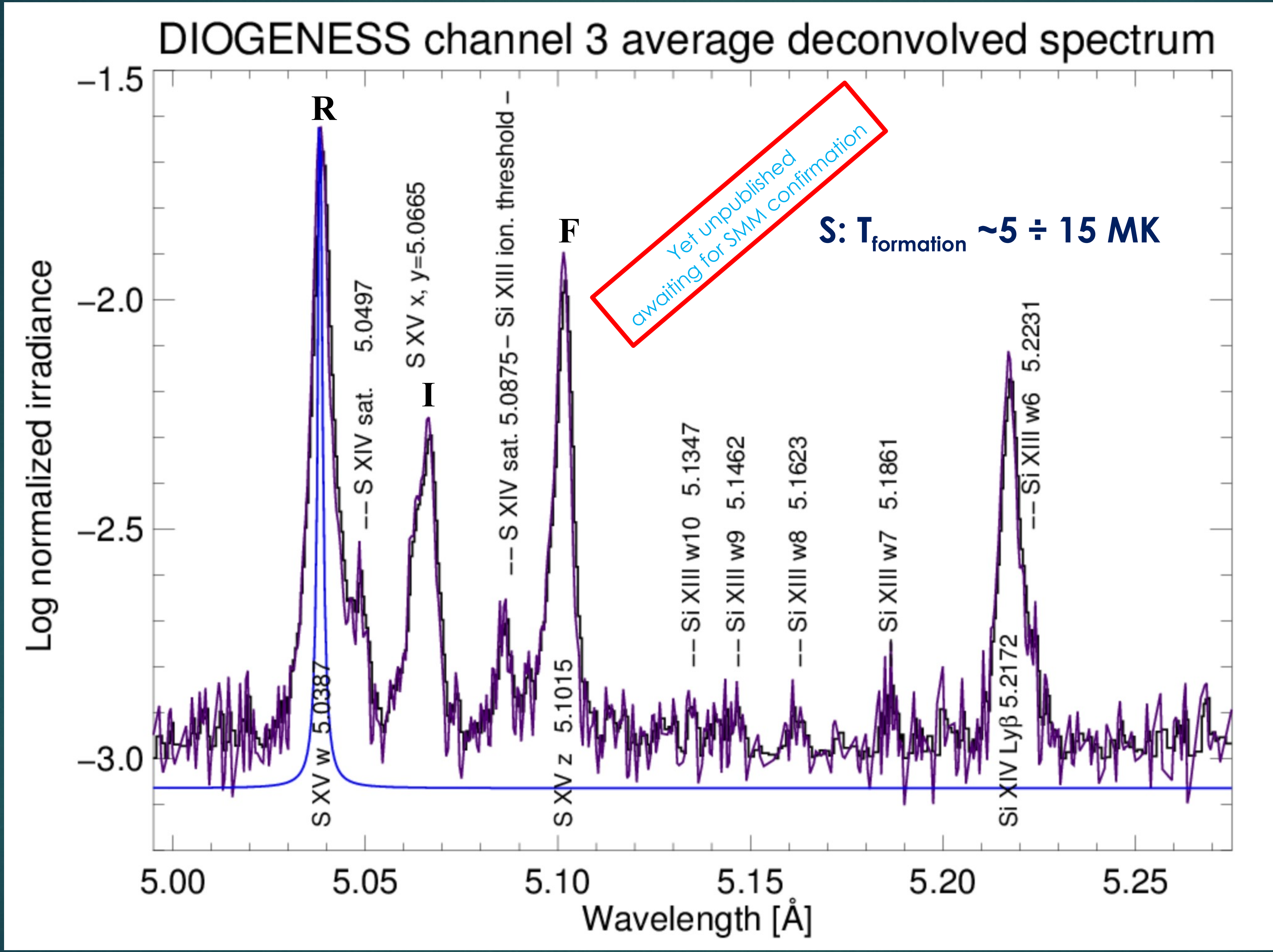




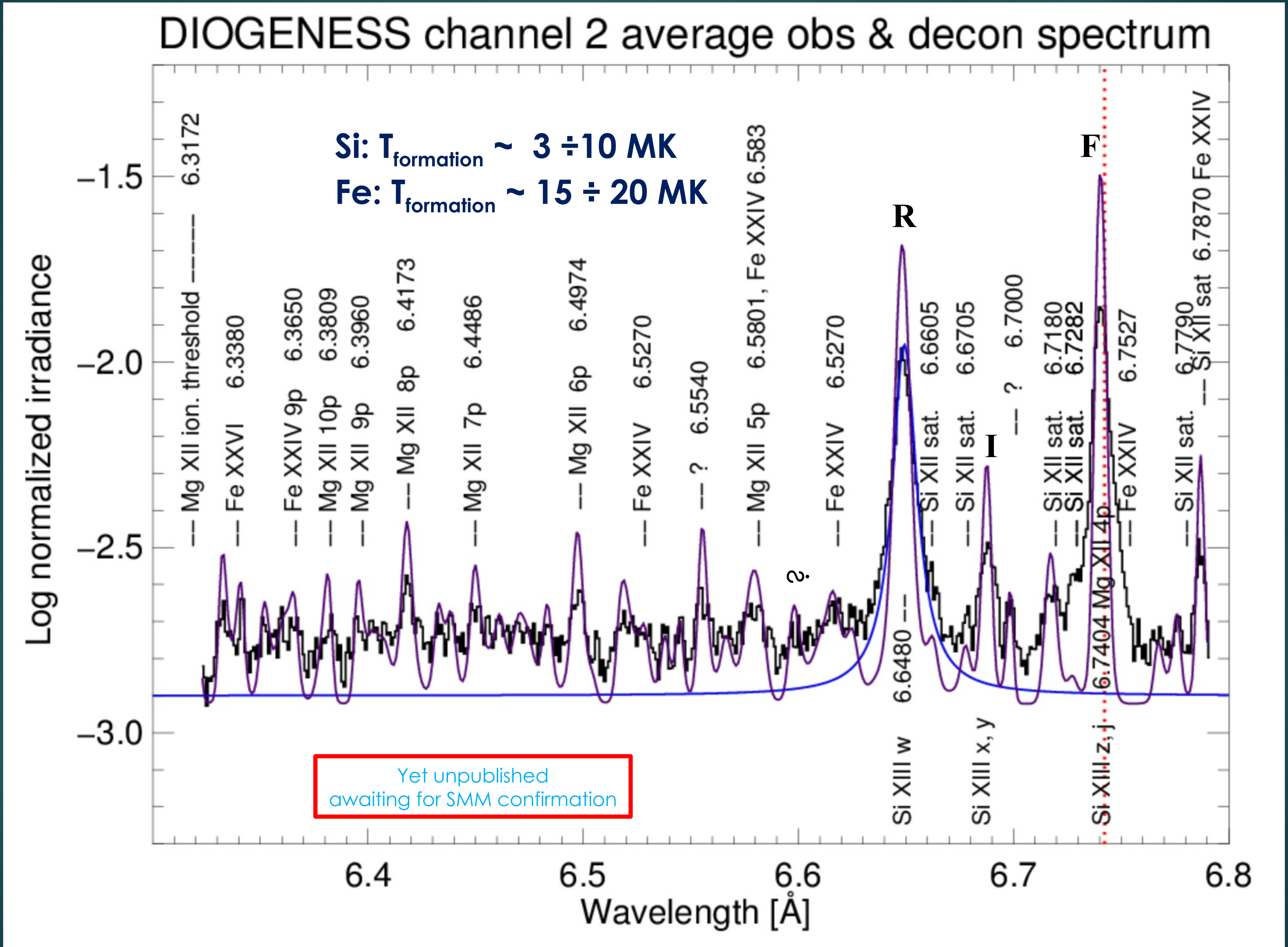




An example of measured spectra recorded nearly simultaneously in Channels #1 and #4 of Diogeness during the maximum phase of X5.3 flare on 25 Aug. 2001. The scanning in both channels is made in the opposite wavelength sense. Thus the intercombination and forbidden lines comprising the Ca XIX triplet are seen on the opposite sides of the presented range (recorded 20 s apart in time).

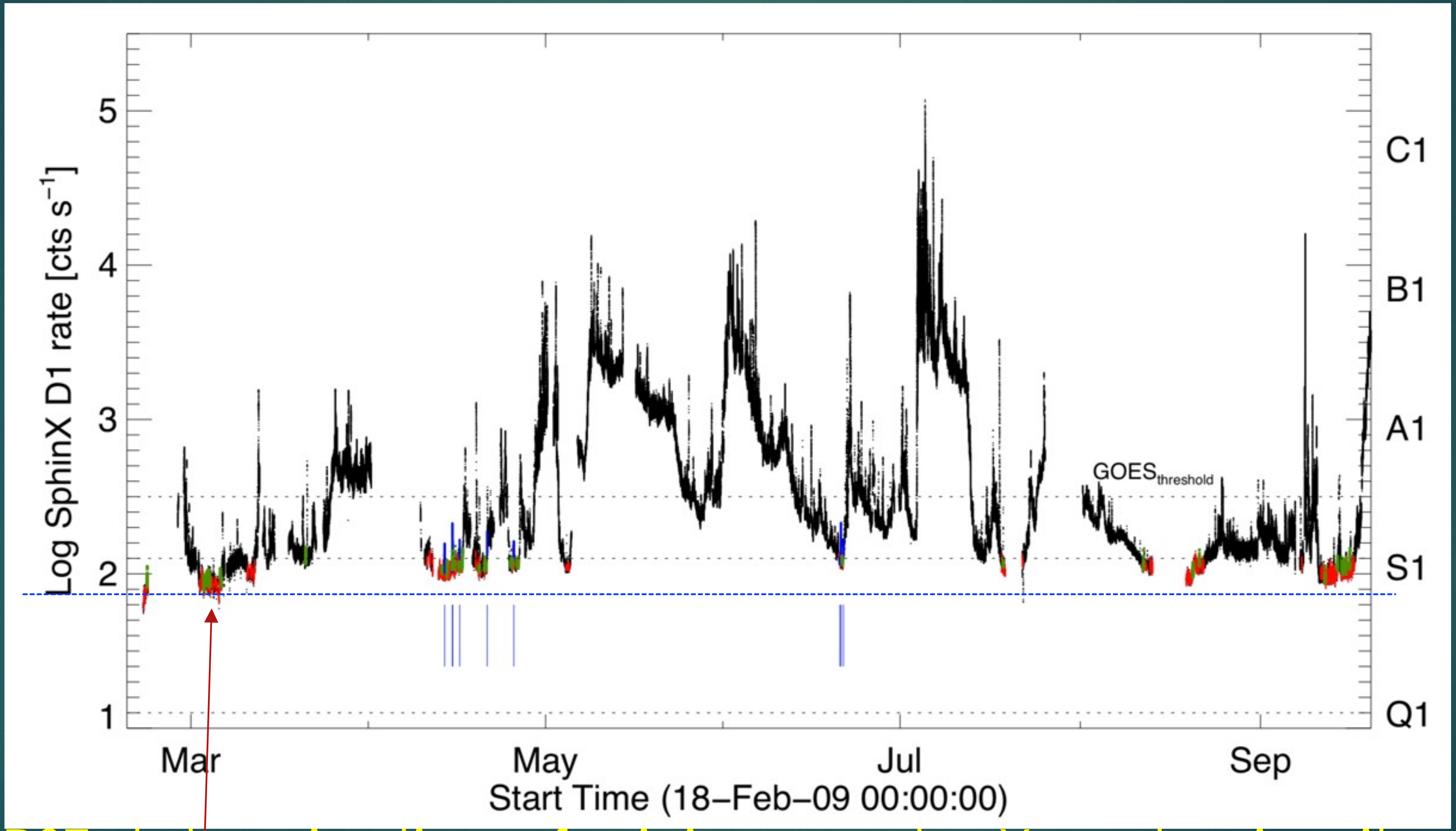
DIOGENESS

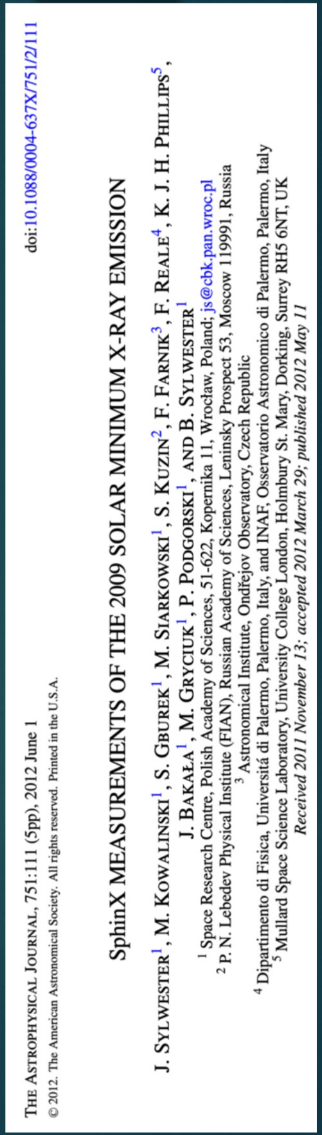


DIOGENESS channel 3 average deconvolved spectrum
Log normalized irradiance
Wavelength [Å]
R
I
F
S XV w 5.0387
S XIV sat. 5.0497
S XV x, y=5.0665
S XIV sat. 5.0875
Si XIII ion. threshold
S XV z 5.1015
Si XIII w10 5.1347
Si XIII w9 5.1462
Si XIII w8 5.1623
Si XIII w7 5.1861
Si XIV Lyβ 5.2172
Si XIII w6 5.2231
Yet unpublished
awaiting for SMM confirmation
S: $T_{formation}$ ~5 ÷ 15 MK


DIOGENESS channel 2 average obs & decon spectrum
Si: $T_{formation}$ ~ 3 ÷10 MK
Fe: $T_{formation}$ ~ 15 ÷ 20 MK
Log normalized irradiance
Wavelength [Å]
Mg XII ion. threshold 6.3172
Fe XXVI 6.3380
Fe XXIV 9p 6.3650
Mg XII 10p 6.3809
Mg XII 9p 6.3960
Mg XII 8p 6.4173
Mg XII 7p 6.4486
Mg XII 6p 6.4974
Fe XXIV 6.5270
? 6.5540
Mg XII 5p 6.5801, Fe XXIV 6.583
Fe XXIV 6.5270
Si XII sat. 6.6605
Si XII sat. 6.6705
? 6.7000
Si XII sat. 6.7180
Si XII sat. 6.7282
Fe XXIV 6.7527
Si XII sat. 6.7790
Si XII sat 6.7870 Fe XXIV
Si XIII w 6.6480
Si XIII x, y
Si XIII z, j 6.7404 Mg XII 4p
R
I
F
Yet unpublished
awaiting for SMM confirmation

# **SphinX**-the most sensitive soft X-ray solar spectrometer put in orbit





THE ASTROPHYSICAL JOURNAL, 751:111 (5pp), 2012 June 1

doi:10.1088/0004-637X/751/2/111

SphinX MEASUREMENTS OF THE 2009 SOLAR MINIMUM X-RAY EMISSION

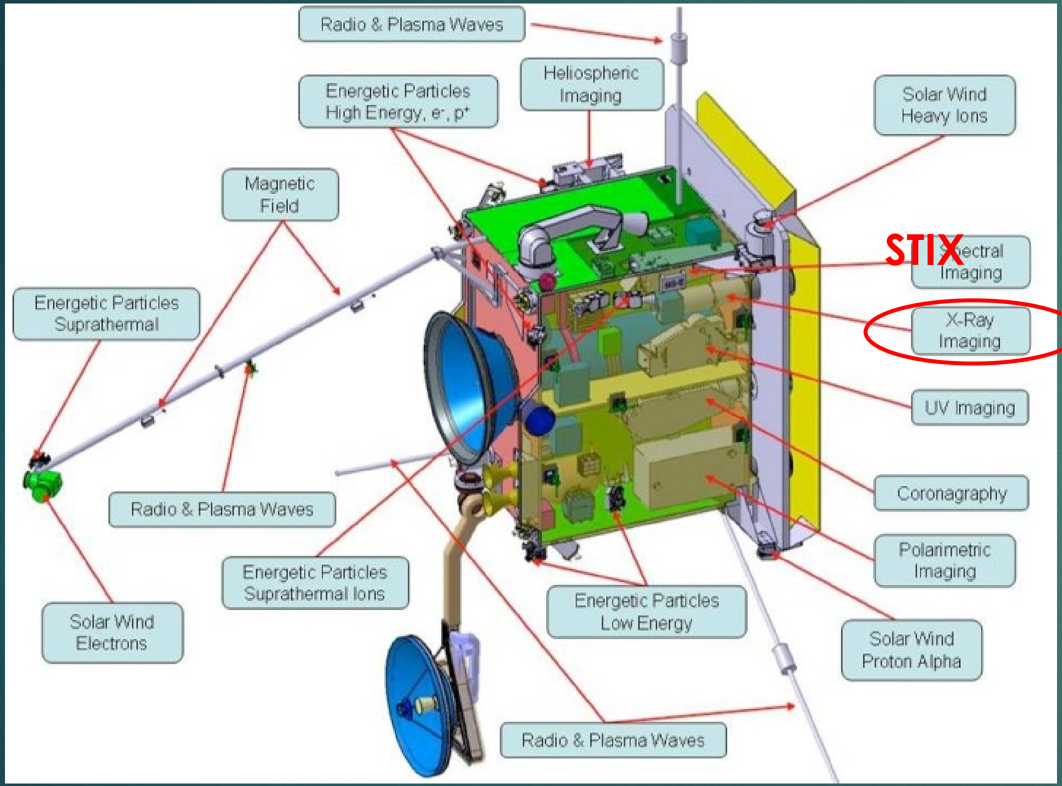
J. SYLWESTER[1], M. KOWALINSKI[1], S. GBUREK[1], M. SIARKOWSKI[1], S. KUZIN[2], F. FARNIK[3], F. REALE[4], K. J. H. PHILLIPS[5],
J. BAKAŁA[1], M. GRYCIUK[1], P. PODGORSKI[1], AND B. SYLWESTER[1]
[1] Space Research Centre, Polish Academy of Sciences, 51-622, Kopernika 11, Wrocław, Poland; js@cbk.pan.wroc.pl
[2] P. N. Lebedev Physical Institute (FIAN), Russian Academy of Sciences, Leninsky Prospect 53, Moscow 119991, Russia
[3] Astronomical Institute, Ondřejov Observatory, Czech Republic
[4] Dipartimento di Fisica, Università di Palermo, Palermo, Italy, and INAF, Osservatorio Astronomico di Palermo, Palermo, Italy
[5] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK
Received 2011 November 13; accepted 2012 March 29; published 2012 May 11

FIRST determination of minimum solar X-ray luminosity

log LRASS = 25.2 (LRASS in erg s−1)

# STIX on Solar Orbiter, the launch took place 2020





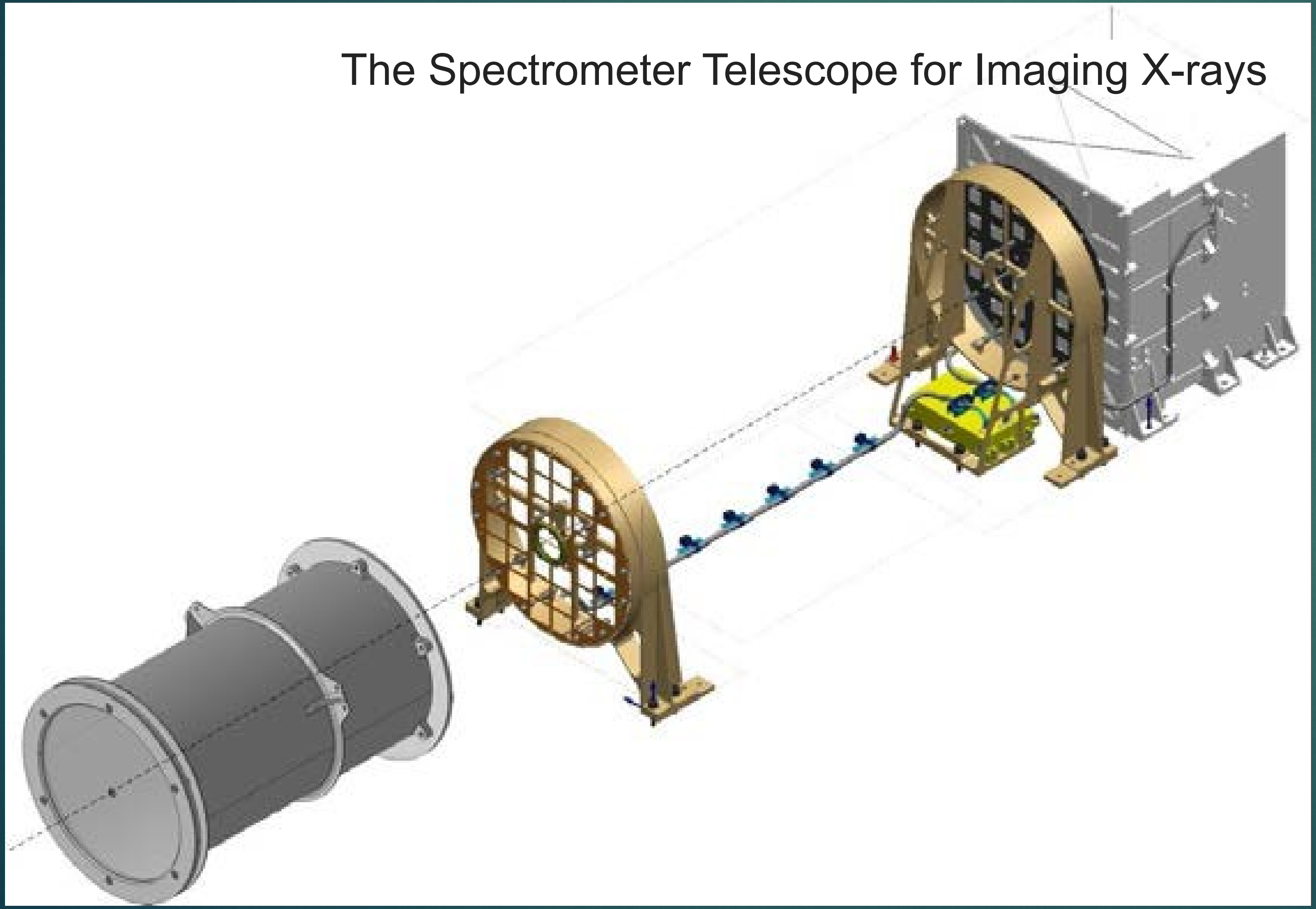

Going down to ~ 0.4 A.U., incl. ~30

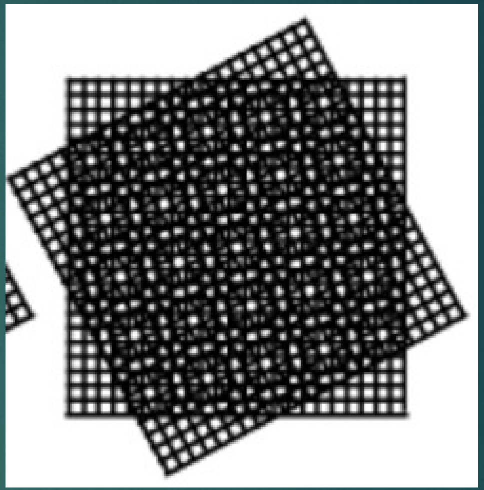
Key people in Poland: Tomek Mrozek, Daniel Scisłowski, Piotr Orleański, Konrad Skup

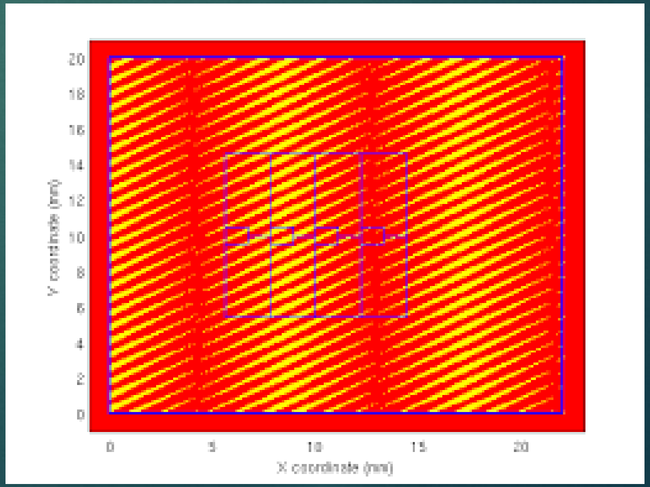
# STIX contributions:

Switzerland 50%, **Poland 30%** , + Germany, France, Czechia, Austria, Ireland

STIX is the Fourier telescope (like radio-interferometer) operating in **hard X-rays**

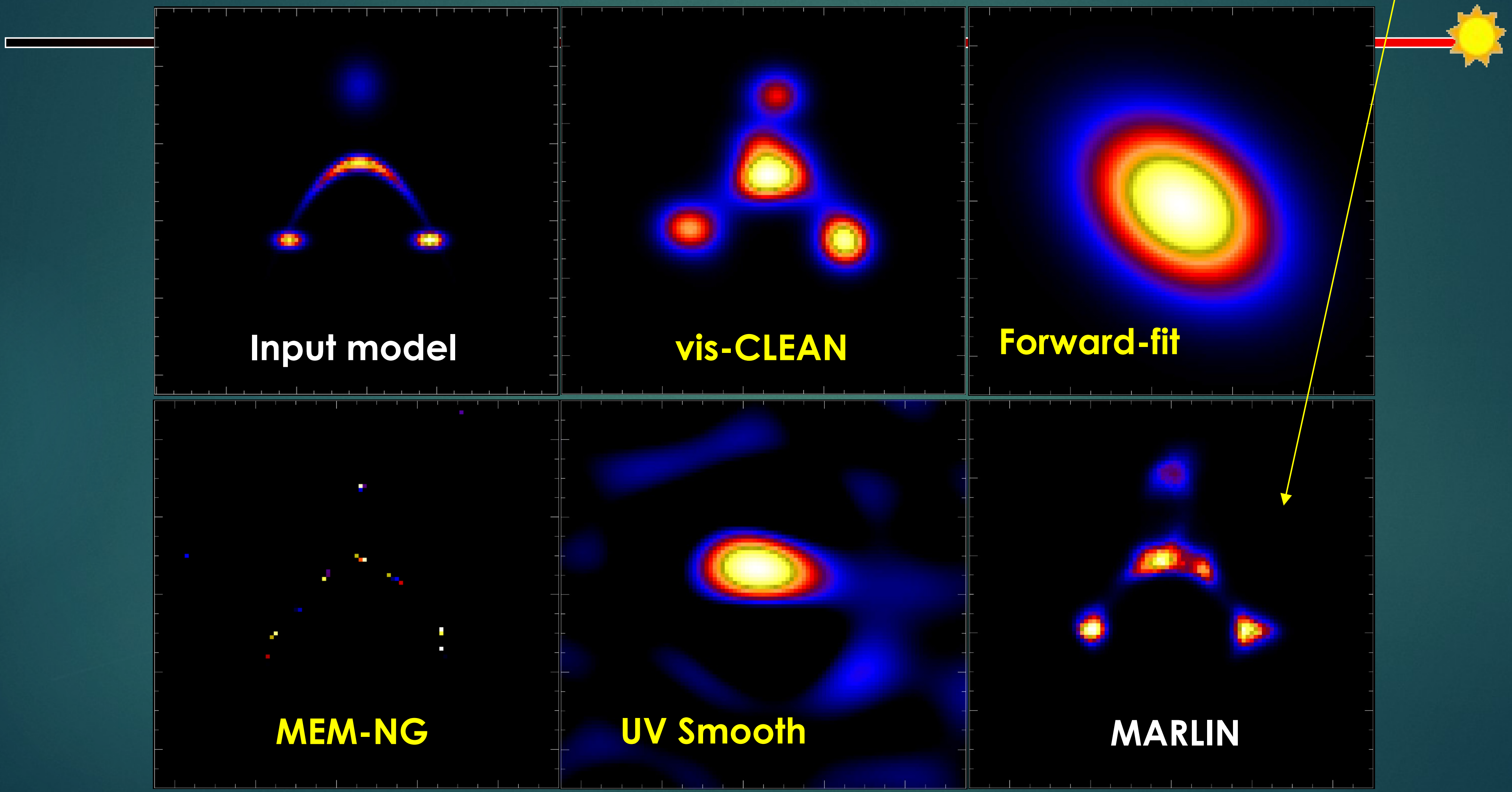


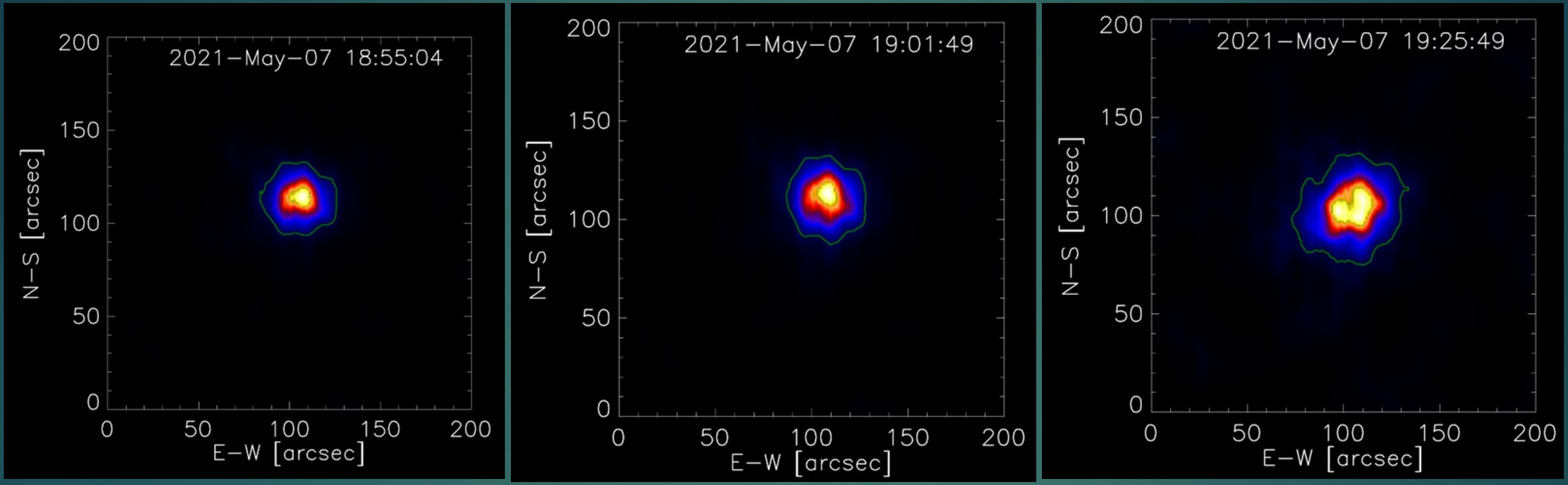


# Wrocław MARLIN algorithm (by Marek Siarkowski)

## wins against competitors



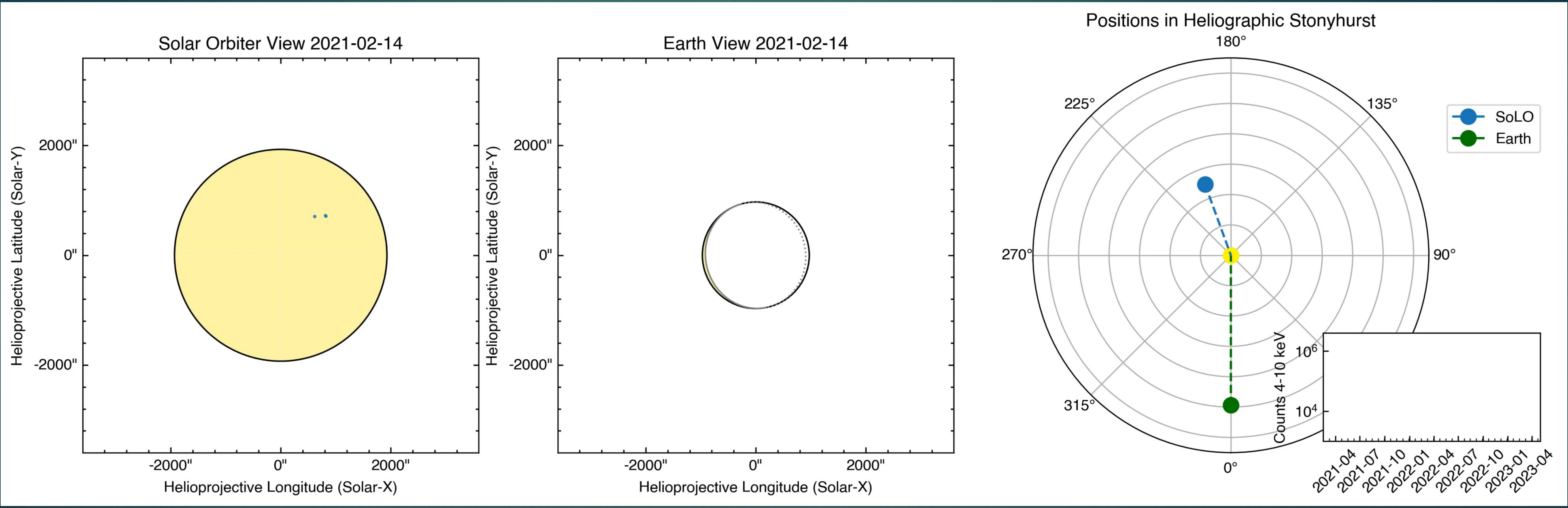
# MARLIN images of a flare from STIX



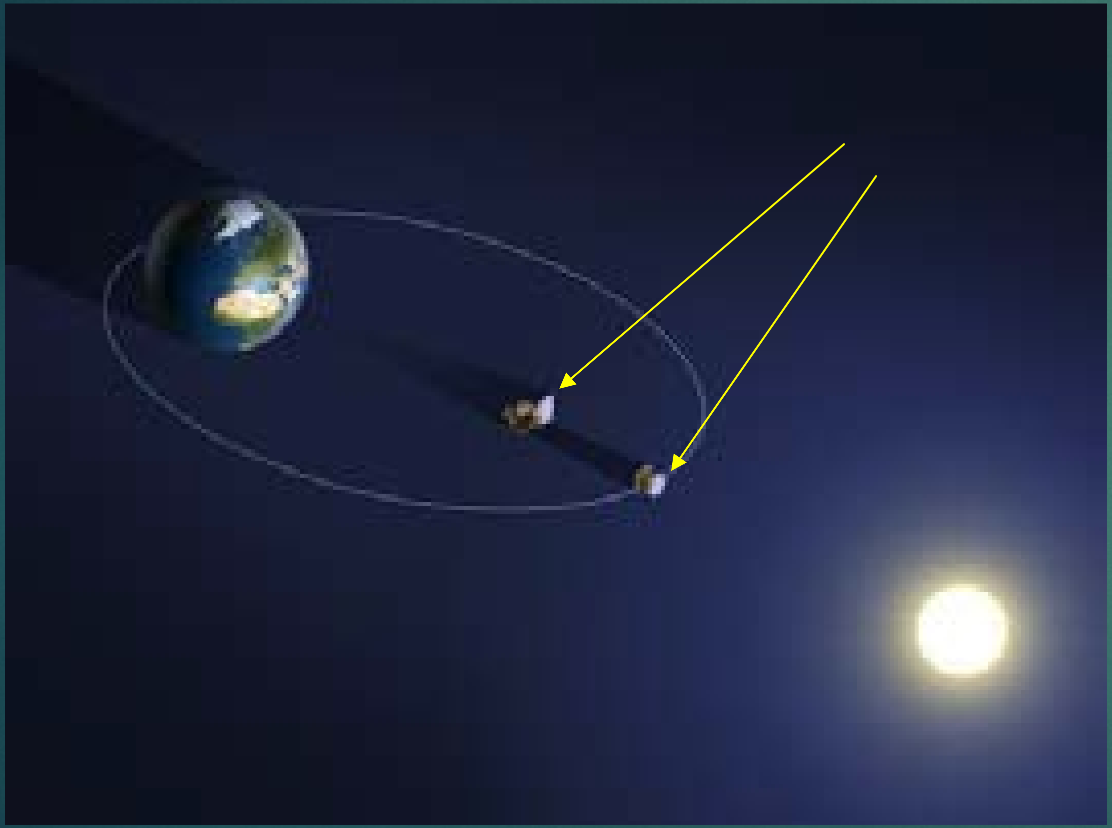

30 000 flares on the record of which 700 with excellent data

# How flares were seen by STIX

## the movie by Laura Hayes (ESA)



# ESA Proba-3, launch 2024 with ASPIICS split coronograph onboard



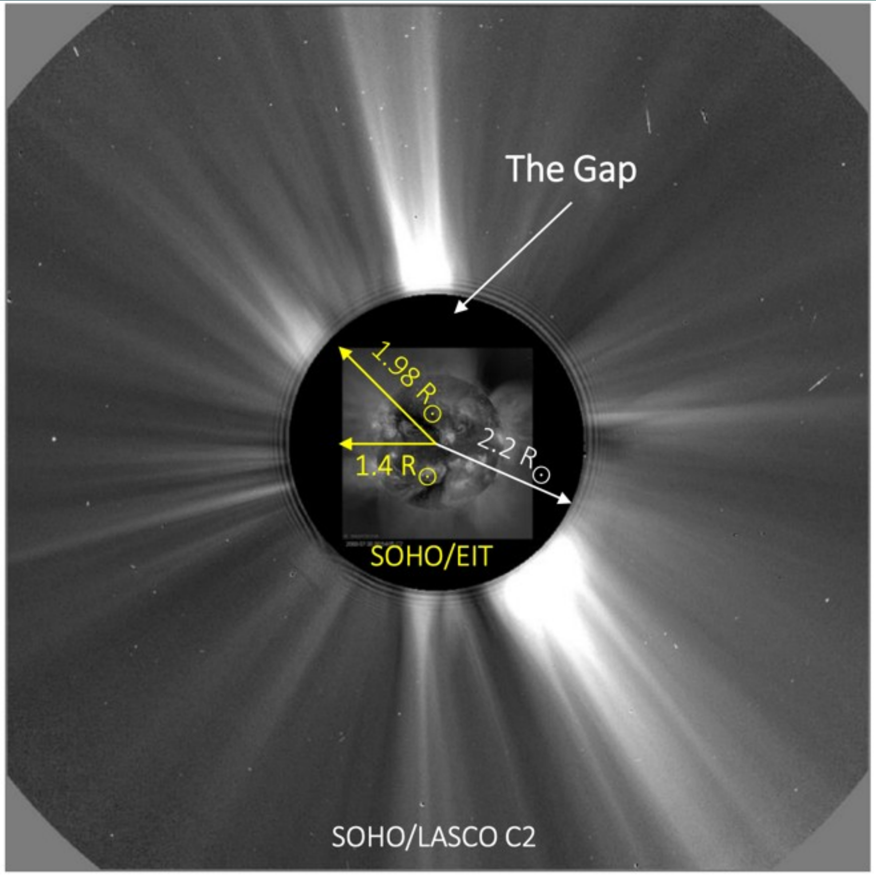
Proba-3 is ESA's – and the world's – first precision **formation flying** mission. A pair of satellites will fly together maintaining a fixed configuration as a 'large rigid structure' in space to prove formation flying technologies.

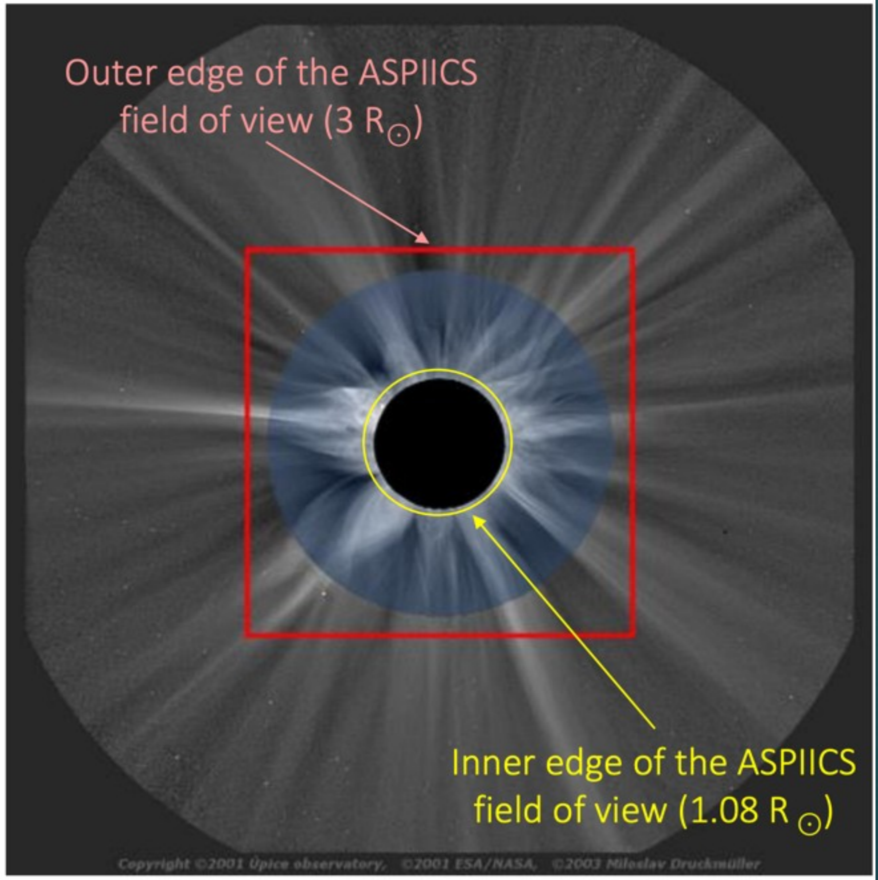
Out of every satellite day (20h) for 6 hours the artificial solar eclipse will be maintained with the corona seen down to **1.08** solar radius

**Poland has a big share** in hardware and software construction . Key people are: Mirosław Rataj, Marek Stęślicki, Ula Stęślicka

http://www.cbk.pan.wroc.pl/body/presentations/2015/Steslicki_Proba3.pdf

# ESA Proba-3, launch 2024 with ASPIICS coronograph onboard




http://www.cbk.pan.wroc.pl/body/presentations/2015/Steslicki_Proba3.pdf

# Over last 50+ years our Laboratory performed these many experiments



- ~10 sounding rocket experiments (PI), 4 satellite experiments (PI)
- Co-I on XRP (SMM-NASA, 1980-1989), BCS (Yohkoh-JAXA, 1991-2001), STIX (on Solar Orbiter)
- PI on RESIK (2001), SphinX (2009), and possibly **BRAXIS** on the next NASA solar Mission (~2030)

- Now consists of
  - 5 PhD post Docs
  - Engineers: mechanical, electronic, software, experimental physics
  - 2 professors
- Published ~300 papers (Nature, ApJ, A&A, Solar Physics)
- We Collaborate with
- US, Swirtzerland,  UK, India, Japan, China, Ukraine

# Thank you

*This work has been possible thanks to the grant of Polish National Science Center*

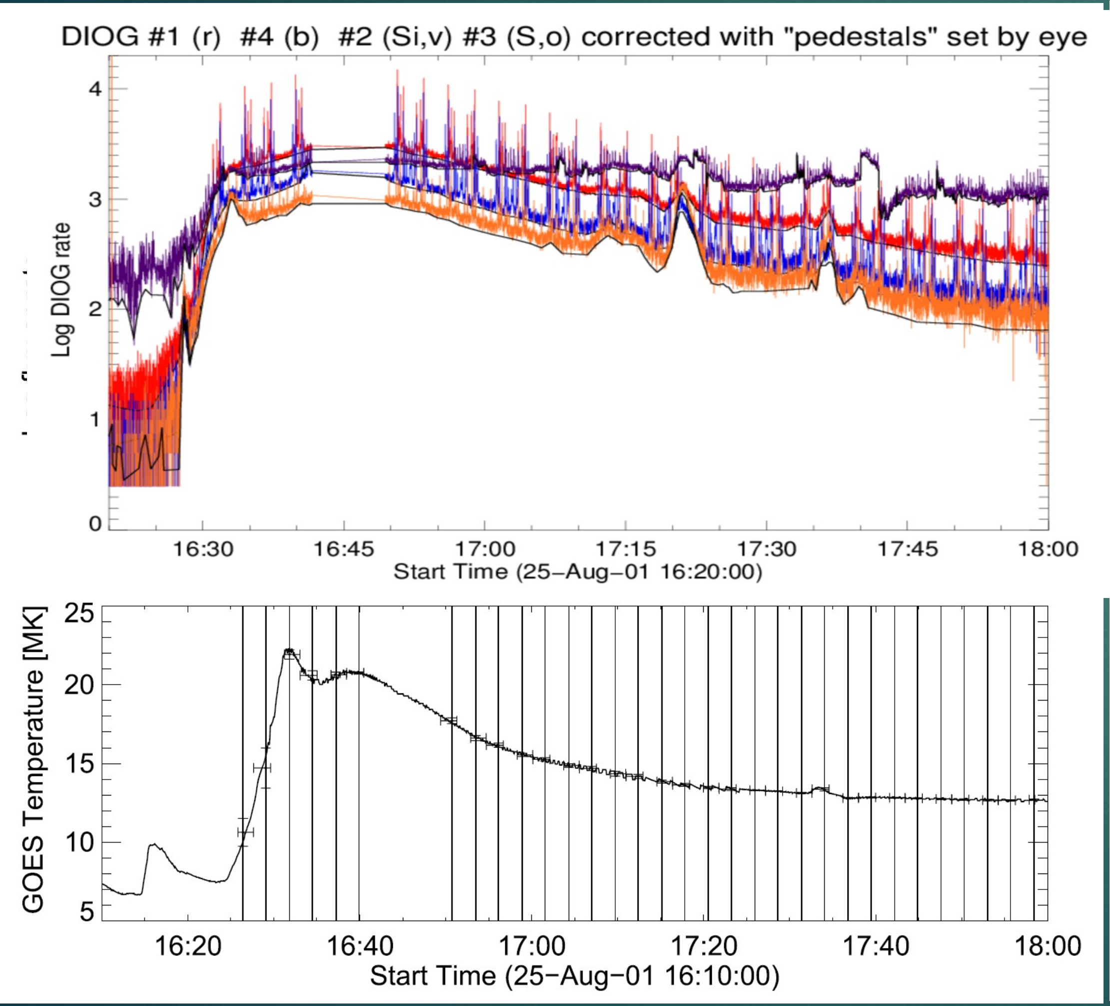
# The bright future we are involved

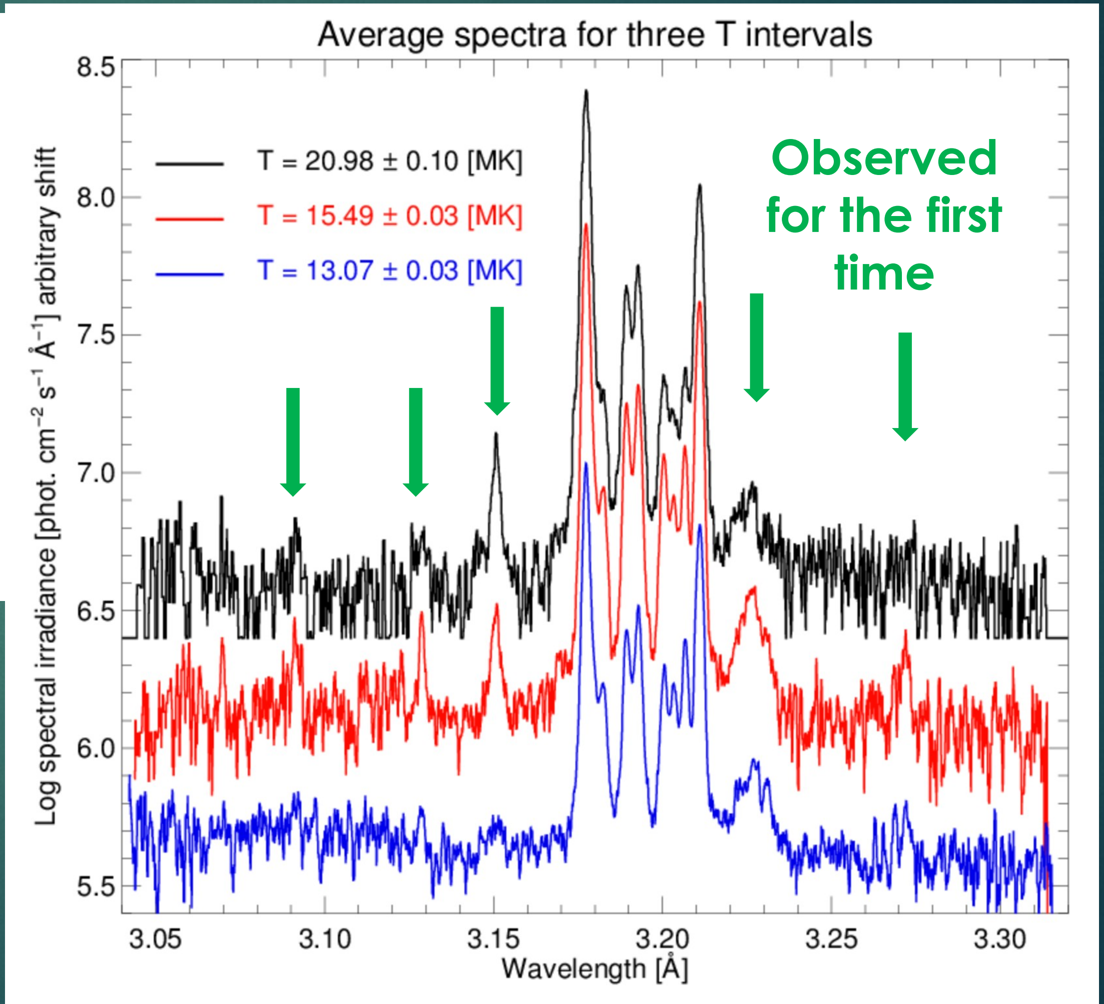


- Recalibration of archive SMM BCS spectra 1980-1989
- STIX on Solar Orbiter, ESA, launch next year
- ASPIICS formation flying coronograph on Proba-3, ESA, launch 2021
- SolpeX for ISS, Russian NAUKA module, launch 2022
- CubiXSS, common nanosatellite with GSFC, Boulder – proposal for NROSES in preparation
- RHESSI NASA follow-up mission

# Ca XIX spectral regions were scanned by two Quartz crystals facing each other, 32 scans exercised

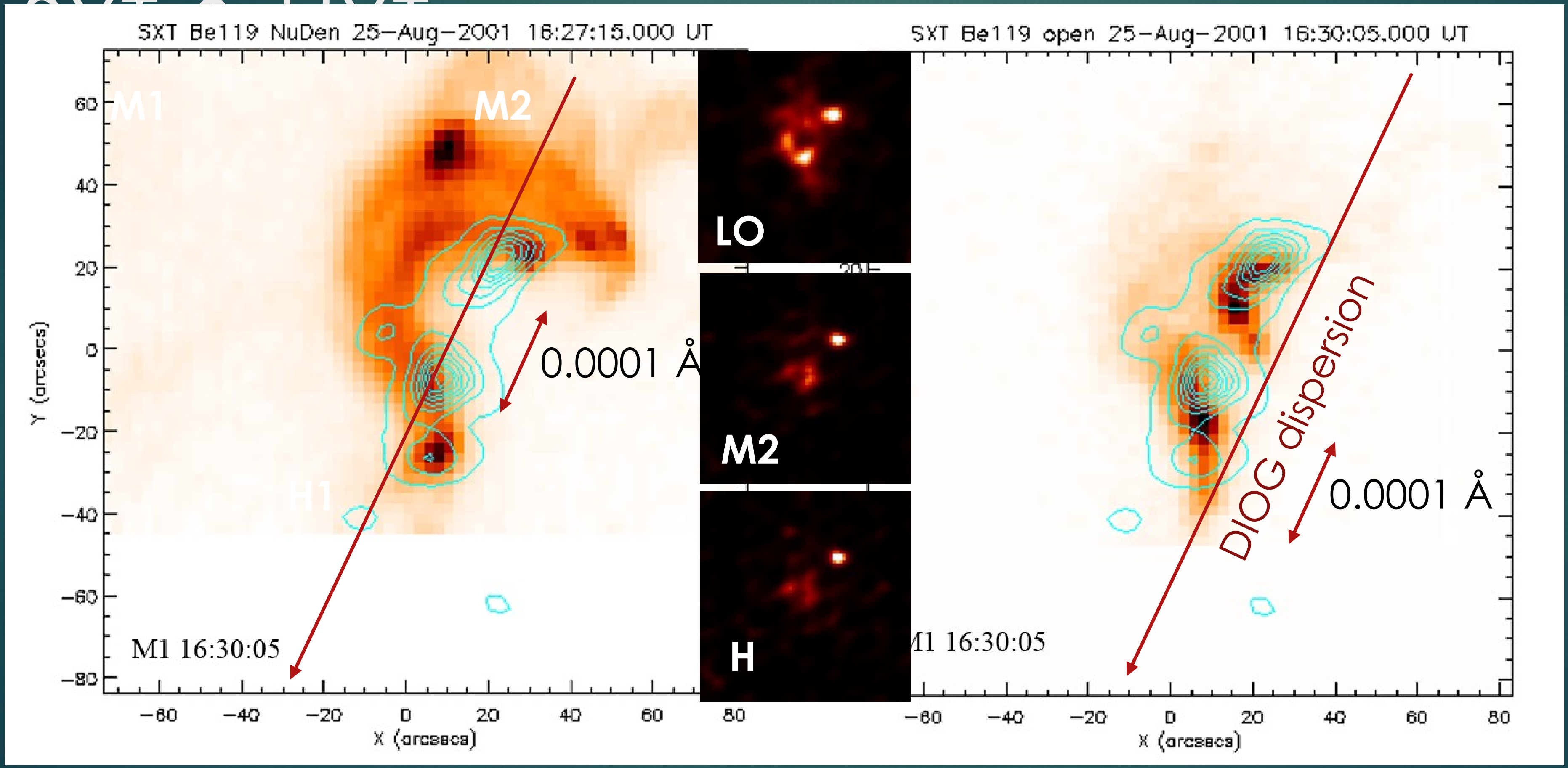
https://doi.org/10.3847/1538-4357/aace5b




The Astrophysical Journal, 863:10 (16pp), 2018 August 10

# Flare of 25 August 2001
# Imaging etc. available from *Yohkoh* SXT & HXT




courtesy Marek Siarkowski and Zbigniew Kordylewski

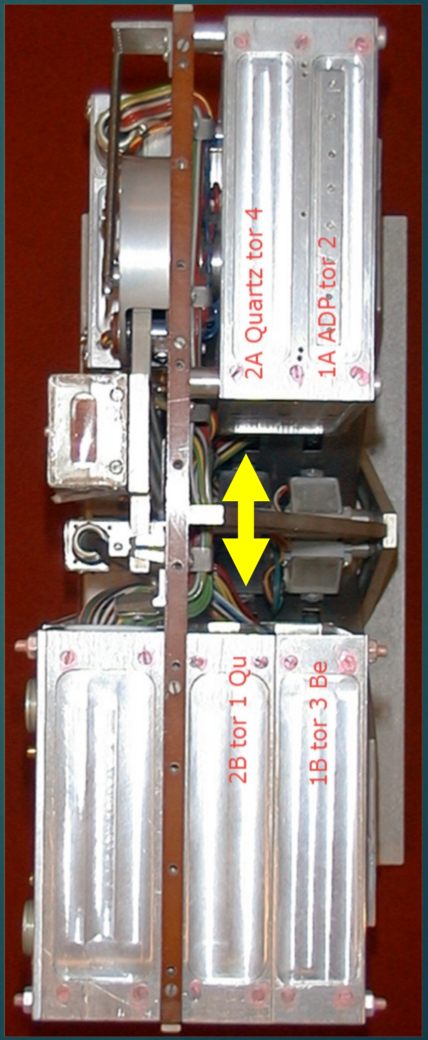
# Diogeness (diagnostics of energy sources & sinks) →4 spectral channels

| Channel | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Crystal | Quartz | ADP | Beryl | Quartz |
| Plane | $10\bar{1}1$ | 101 | $10\bar{1}0$ | $10\bar{1}1$ |
| $2d_1$ Å | 6.6855 | 10.5657 | 15.9585 | 6.6875 |
| $\lambda_{obs}$ [ Å] | 3.1779 | 5.0348 | 6.6492 | 3.1779 |
| $\lambda_{theor}$ [ Å] | 3.1781 | 5.0374 | 6.6488 | 3.1781 |
| Line | Ca XIX | S XV | Si XIII | CaXIX |
| $\lambda_{min}$ [ Å] | 3.1436 | 4.9807 | 6.1126 | 2.9601 |
| $\lambda_{max}$ [ Å] | 3.3915 | 5.3721 | 6.7335 | 3.2123 |
| $R_C$ [$\mu$rd] | 91 | 91 | 15 | 90 |
| FWHM [arcsec] | 24.1 | 68.1 | 94.1 | 25.6 |

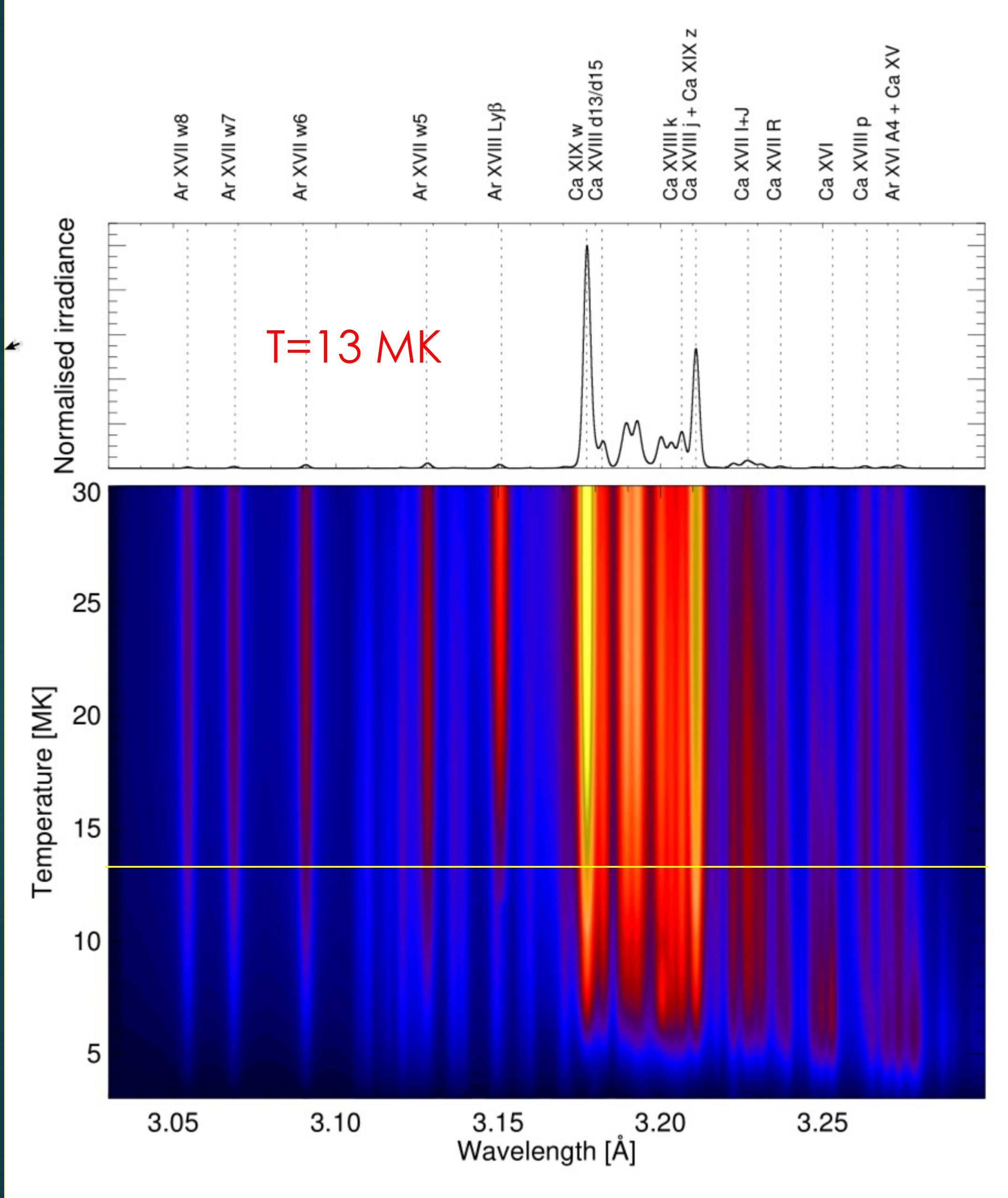
**$R_C$** - The total reflection coefficient.

Bragg law in action

$= 2d \sin\theta$



# Calculations of synthetic spectra arrays (**KJHP+CHIANTI**)




Extensive use of:

- Gabriel, 1972 theory
- Bely-Dubau et al., 1982
- Vainstein & Safronova, 1978
- **Cowan** atomic code, 1981
- CHIANTI formulae for continuum
- CHIANTI (Bryans) modified ionisation equilibrium

2000+ satellite lines additionally calculated using Cowan Hartree-Fock distorted-wave approximation

Assumed ratio of $A_{Ar}/A_{Ca}$ **= 0.33 !!!**

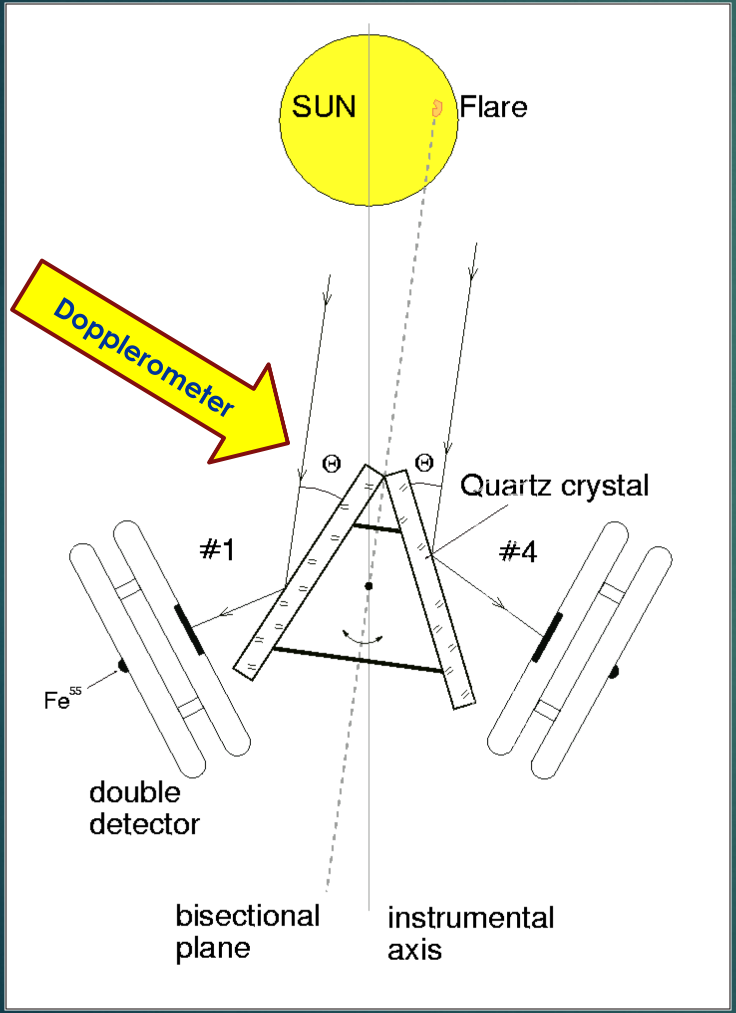
$A_{Ca}$ based on **SMM BCS** (Sylwester et al. 1998, ApJ 501, 397)

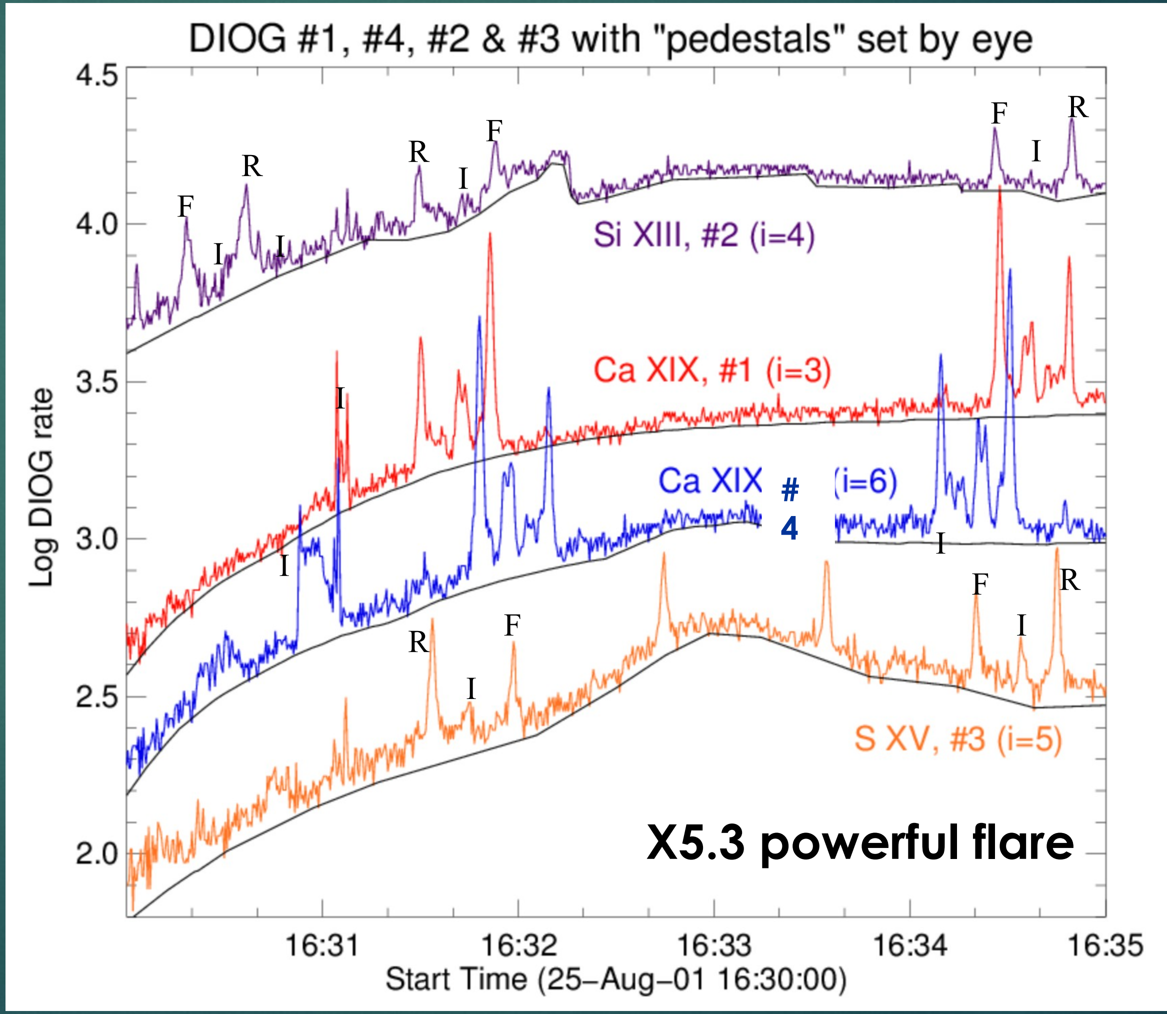
$A_{Ar}$ from RESIK spectra (Sylwester et al., 2010, ApJ 720, 1721)

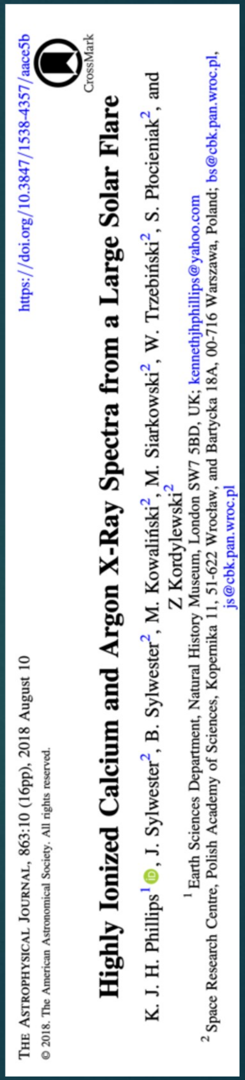
# Spectra recorded using Bragg flat-crystal monochromators

= 2d sin$\theta$

DIOGENESS





The Astrophysical Journal, 863:10 (16pp), 2018 August 10
https://doi.org/10.3847/1538-4357/aace5b


**Highly Ionized Calcium and Argon X-Ray Spectra from a Large Solar Flare**

K. J. H. Phillips[1], J. Sylwester[2], B. Sylwester[2], M. Kowaliński[2], M. Siarkowski[2], W. Trzebiński[2], S. Płocieniak[2], and Z Kordylewski[2]
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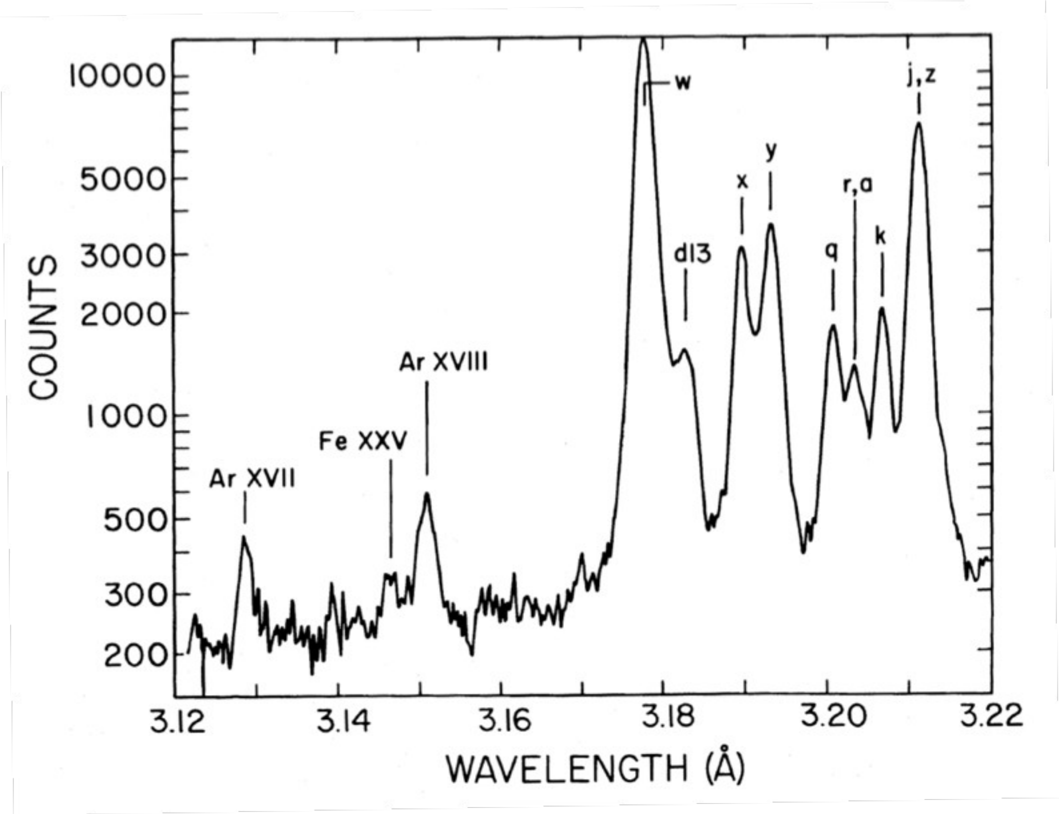
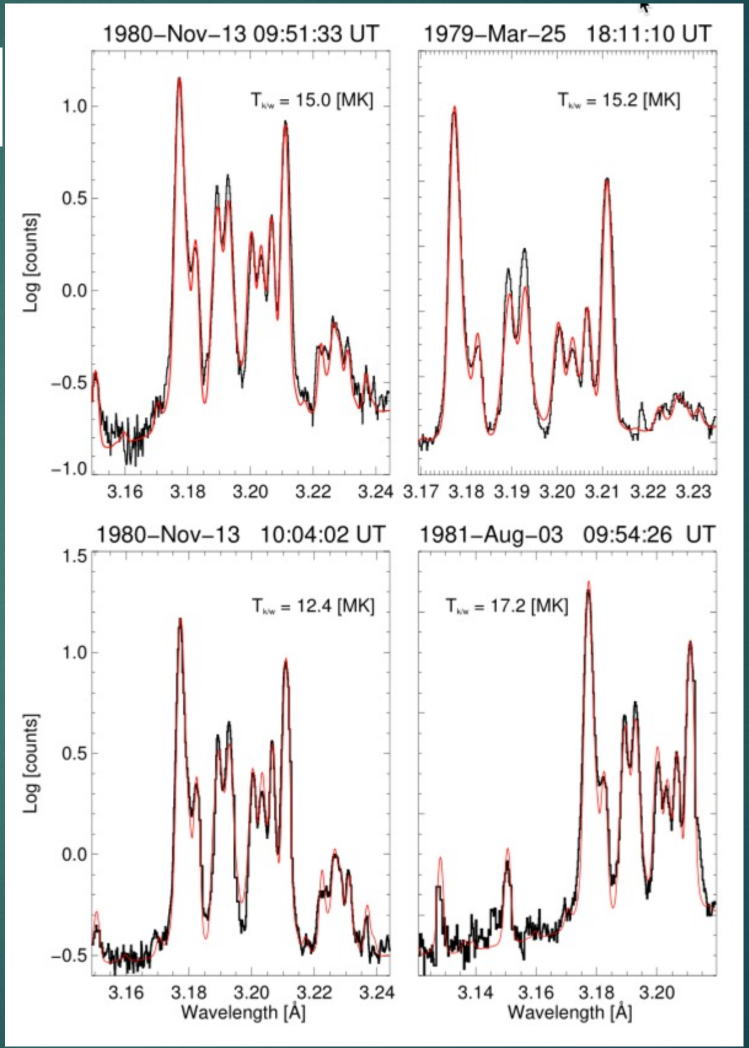
# Fits to NRL P78-1 SOLFLEX spectra (1979-1981)

THE ASTROPHYSICAL JOURNAL, 338:567–577, 1989 March 1


MEASUREMENT OF WAVELENGTHS FOR INNER-SHELL TRANSITIONS IN Ca XVII–XIX

J. F. SEELY AND G. A. DOSCHEK




Thanks Jarek Bąkała for digitisation

# Motivation



- Observations of hot, multimilion degrees upper layers of solar atmosphere provide direct insight into possible physical processes of energy release with unprecedented spatial, spectral & time resolution (~tens km, 0.0001 Å, 0.1 s)
  - Magnetic reconnection
  - Deposition of wave energy generated in the convection zone
- Active regions and flares are the sources of intense X-ray emission which can be studied using relatively small instruments
  - Soft X-ray spectra $\lambda$ ~1.5 – 25 Å ( E ~0.5 – 10 keV) are most of the time thermal
  - Hard X-ray spectra (E > 15 keV) contain important non-thermal contribution
- High-resolution X-ray spectra contain strong emission lines which intensity & shapes provide direct insight into physical conditions in the source plasma
  - Elemental abundances
  - Bulk & turbulent plasma motions
  - Electron and ion temperatures, distribution of plasma in various temperatures (differential emission measure, DEM)
- Emanating solar radiation & particle flux determine the physical conditions in the heliosphere, in particular the space weather around planets including the Earth. Magnetic storms caused by solar activity may cause havoc for our civilization
  - Power outages
  - Radio communication