Latest RHESSI (Ramaty High Energy Solar Spectroscopic Imager) Results on Particle Acceleration and Energy Release in Solar Flares

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The Sun is the most energetic particle accelerator in the solar system

Ions up to ~ 10s of GeV

Electrons up to ~100s of MeV

At the Sun:

* ***Solar Flares – the most powerful explosions in the solar system***

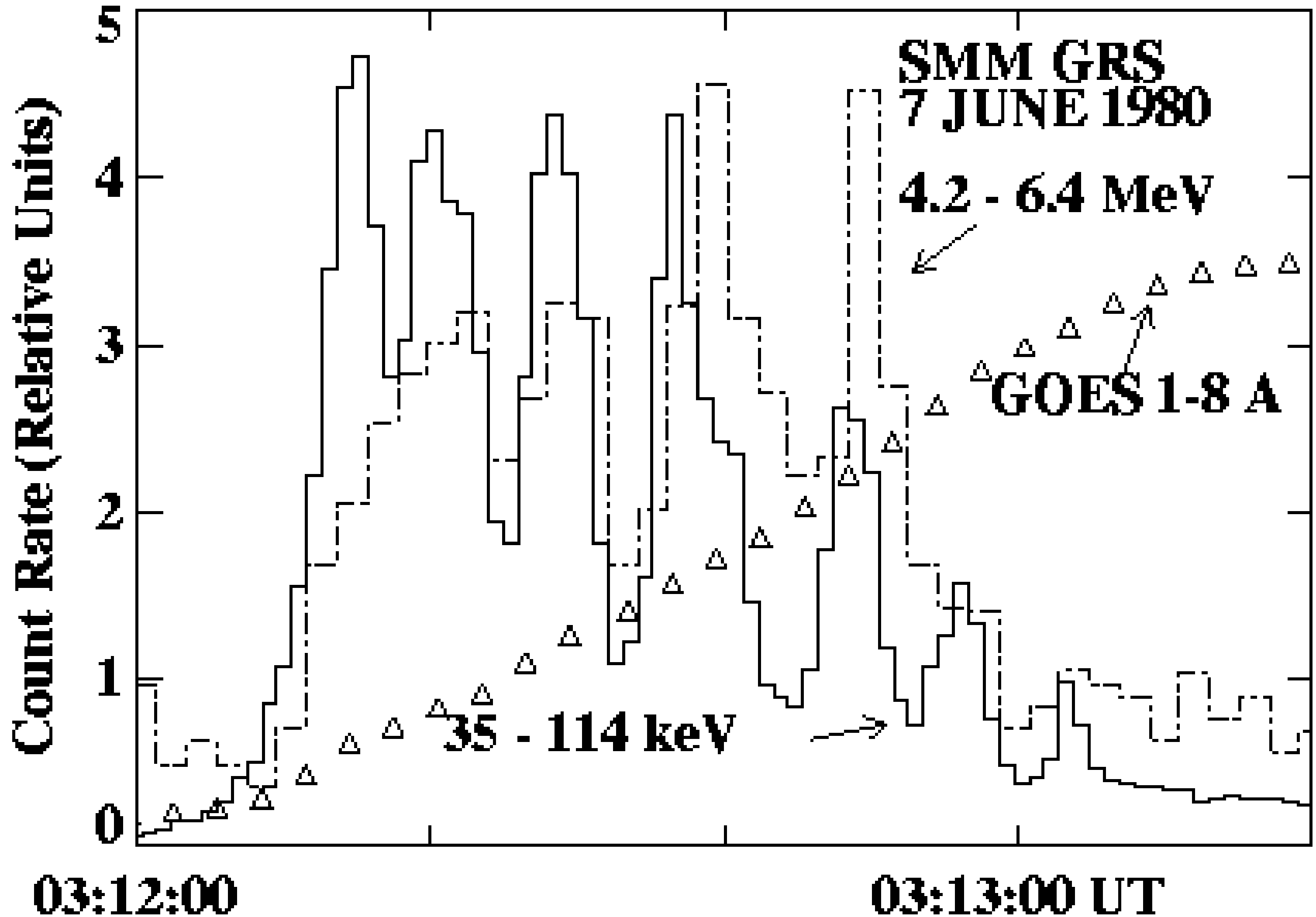
Release up to ~ 10^{32} - 10^{33} ergs in ~ 10 – 10^{3} seconds

Flare-accelerated ~20-100 keV electrons contain ~10-50% of energy released

>~1 MeV ions may contain comparable energy

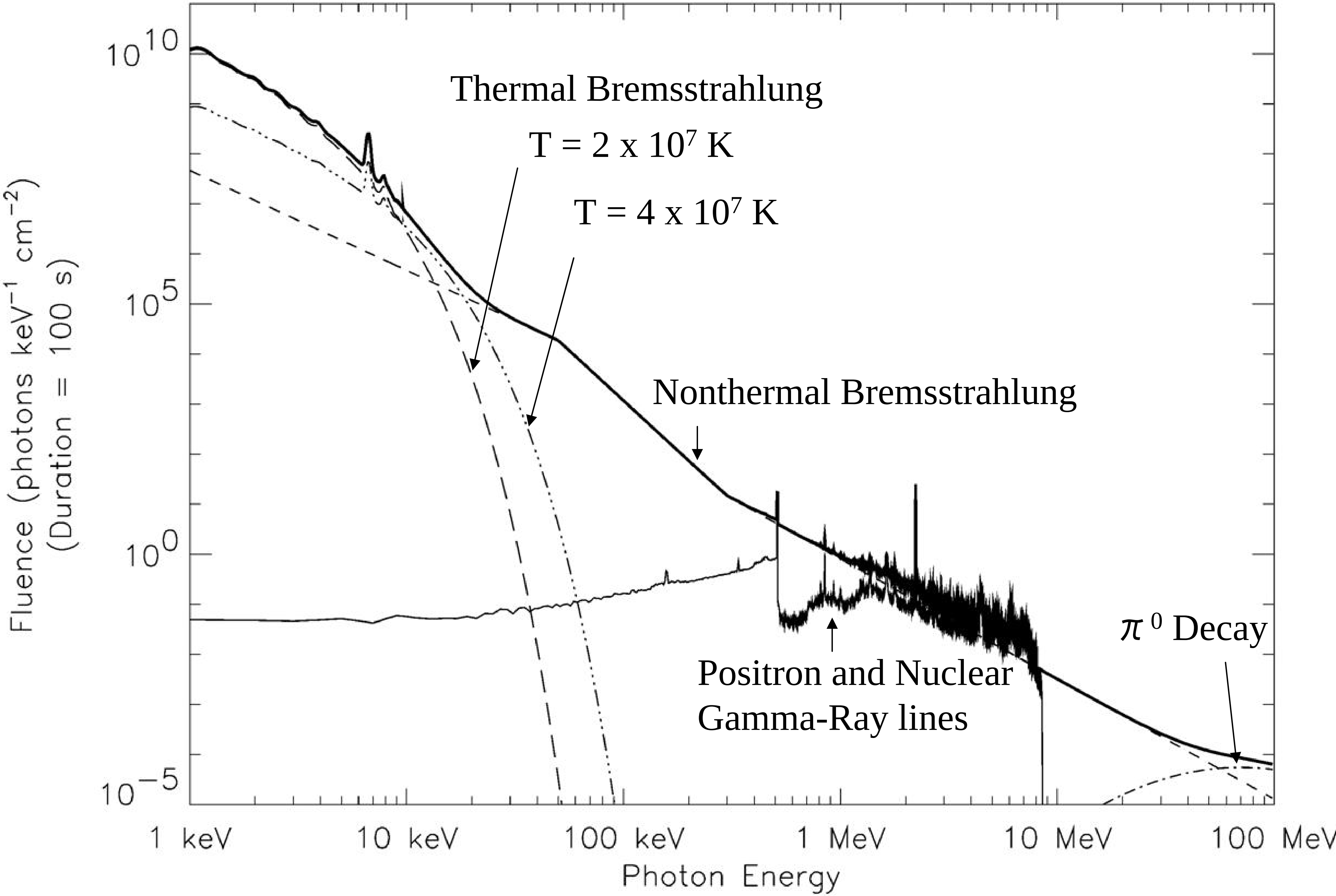
*=> **Acceleration is intimately related to flare energy release***

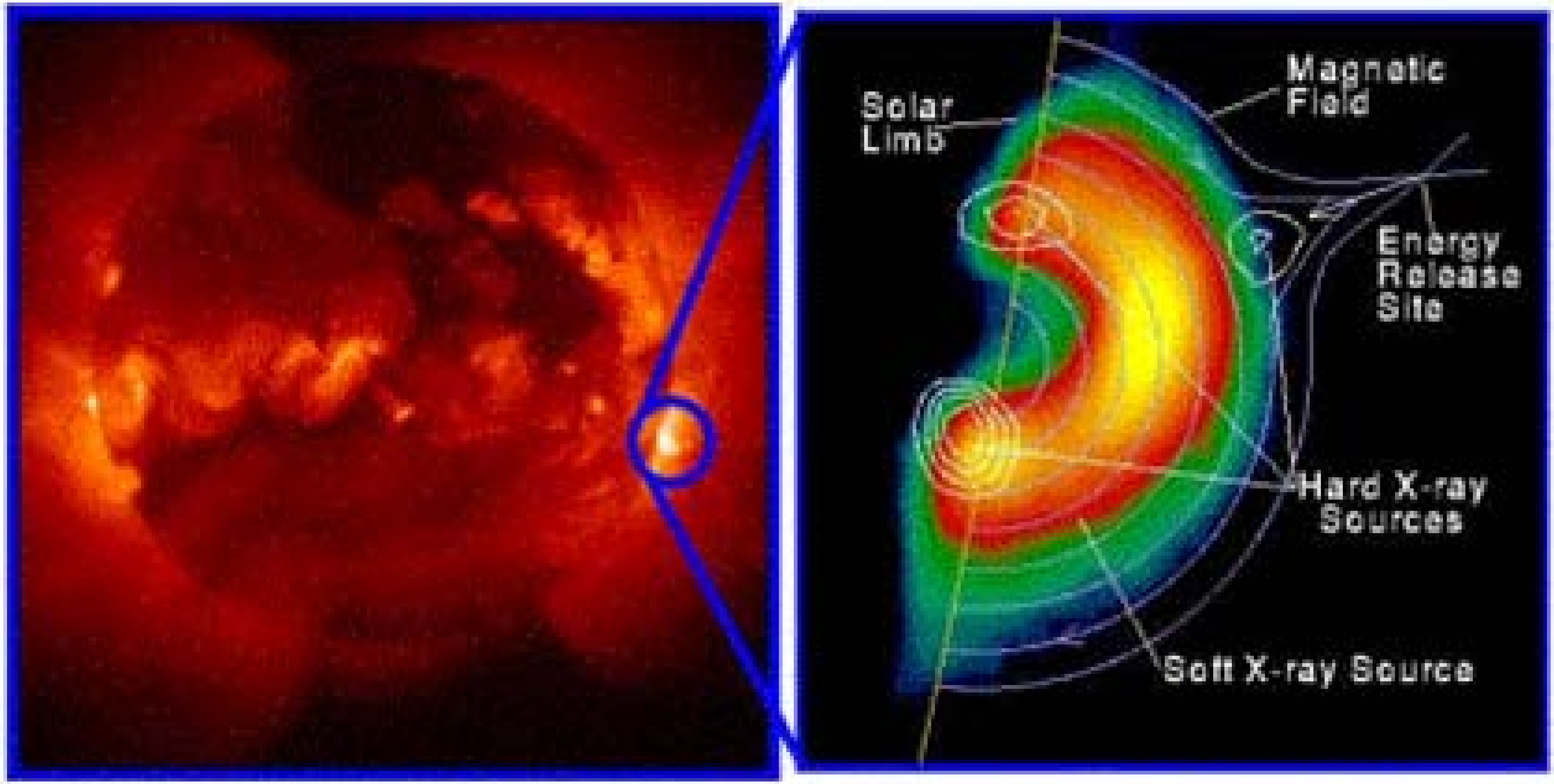
* ***Energy released by flares -> microflares -> nano-flares may be significant for heating of the solar corona***



SMM GRS
7 JUNE 1980
4.2 - 6.4 MeV
GOES 1-8 A
35 - 114 keV
Count Rate (Relative Units)
0
1
2
3
4
5
03:12:00
03:13:00 UT

Composite Solar Flare Spectrum

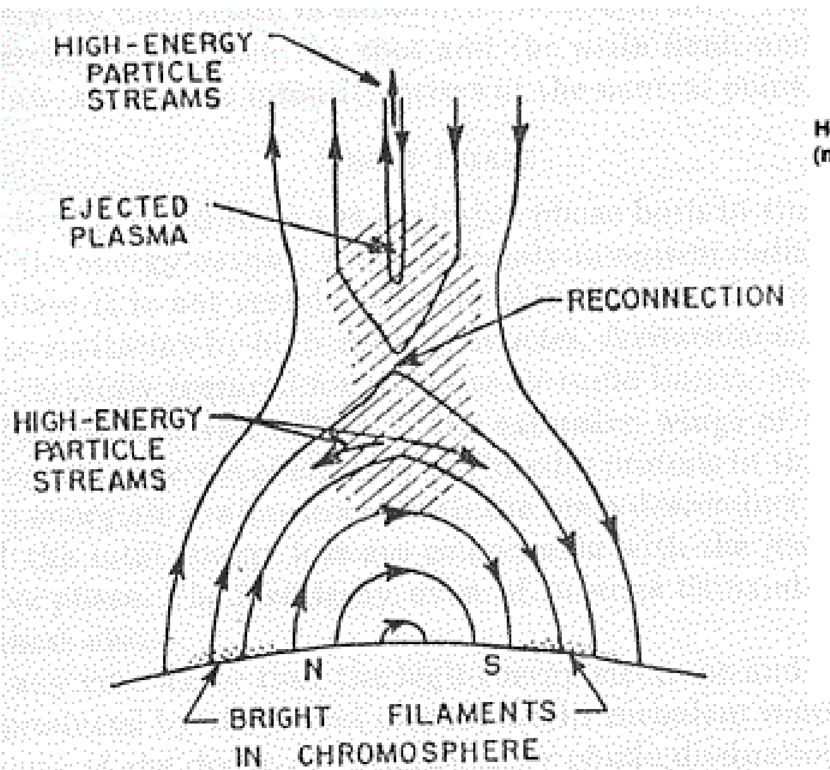




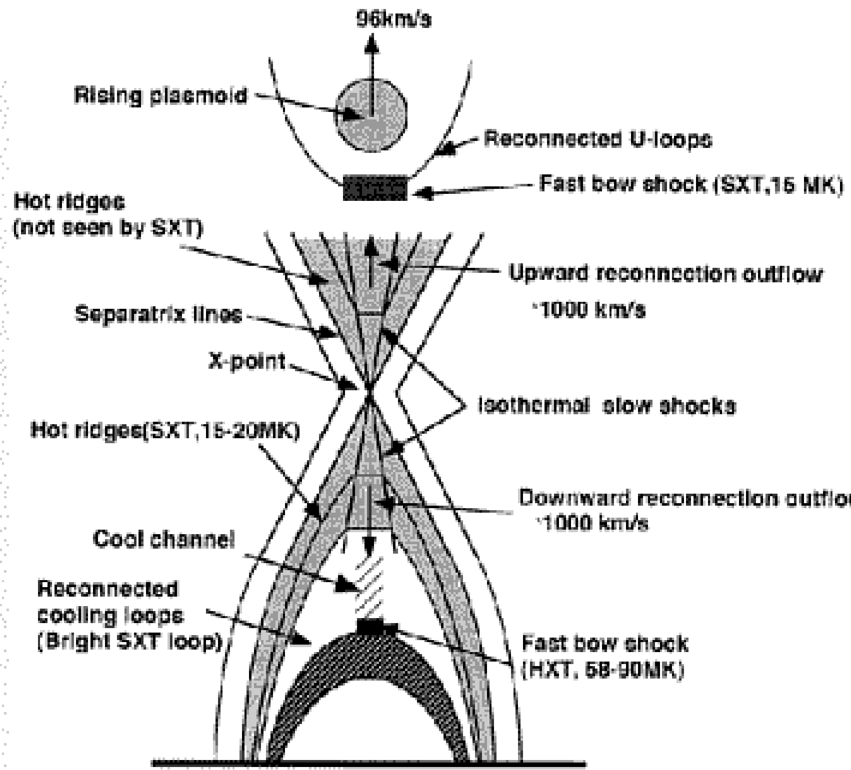
Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.

‘Standard’ model

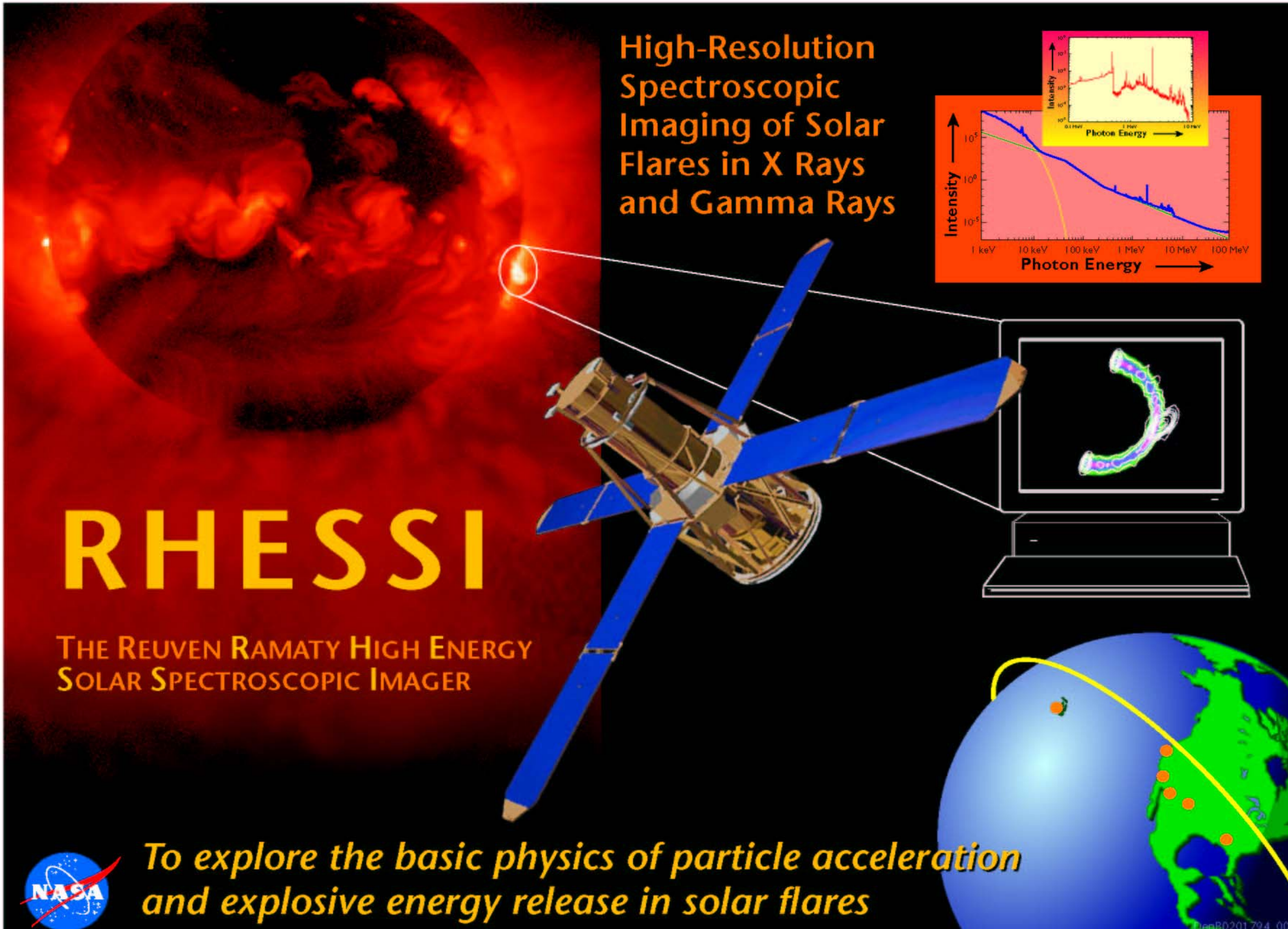
This has evolved to keep pace with observations



Sturrock 1966



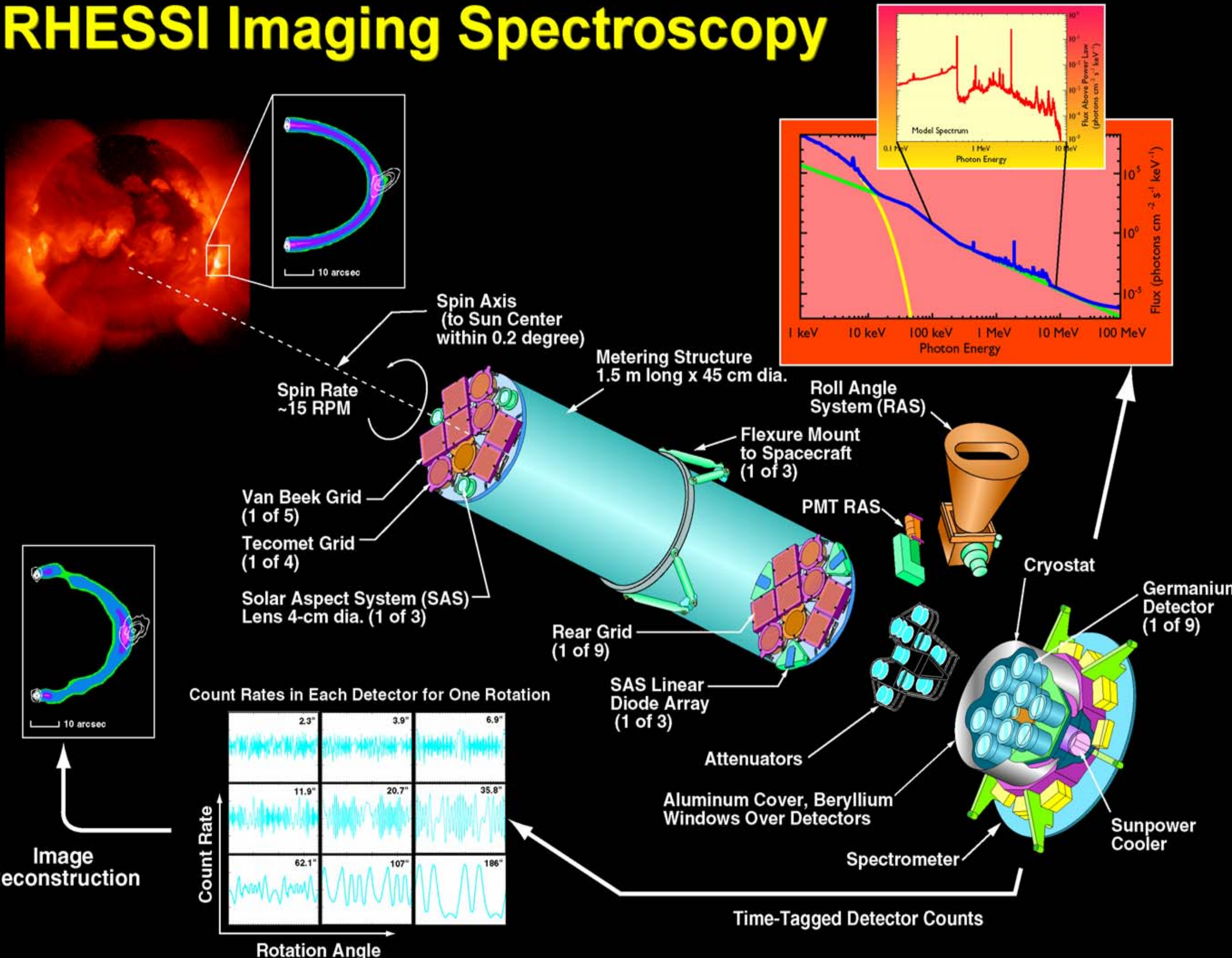
Tsuneta 1997


High-Resolution Spectroscopic Imaging of Solar Flares in X Rays and Gamma Rays
Intensity
Photon Energy
Intensity
1 keV
10 keV
100 keV
1 MeV
10 MeV
100 MeV
Photon Energy
RHESSI
THE REUVEN RAMATY HIGH ENERGY SOLAR SPECTROSCOPIC IMAGER
NASA
To explore the basic physics of particle acceleration and explosive energy release in solar flares

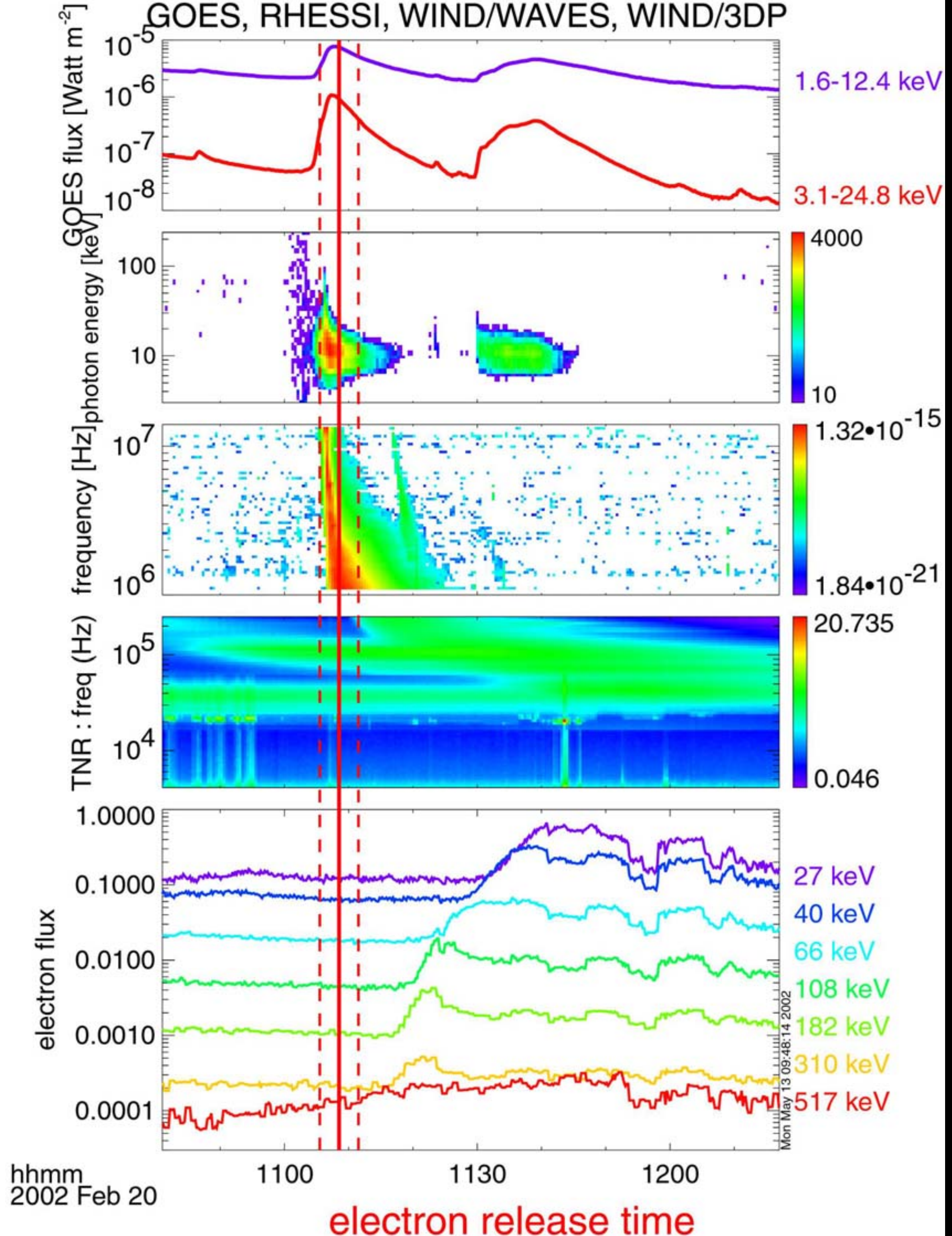
Reuven Ramaty
1937 – 2001

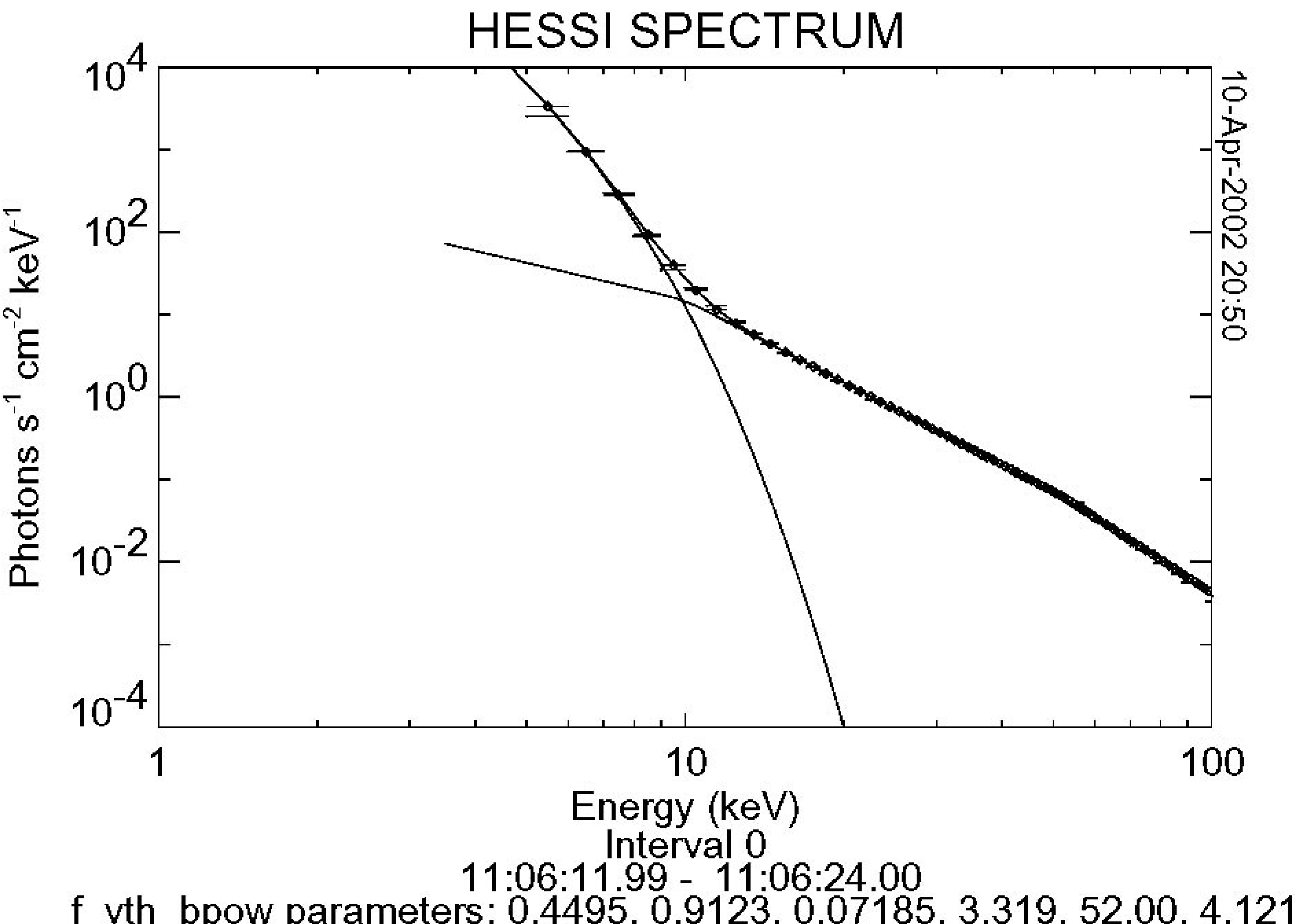
Dr. Ramaty was a pioneer in the fields of solar physics, gamma-ray astronomy, nuclear astrophysics, and cosmic rays.
He was a HESSI Co-I and one of the founding members of the HESSI team.
His active involvement and enthusiastic support were critical for HESSI's selection by NASA as the sixth Small Explorer (SMEX) mission.
Following the launch on February 5, 2002, HESSI was renamed in his honor.
It became the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), the first space mission named after a NASA scientist.

RHESSI Imaging Spectroscopy

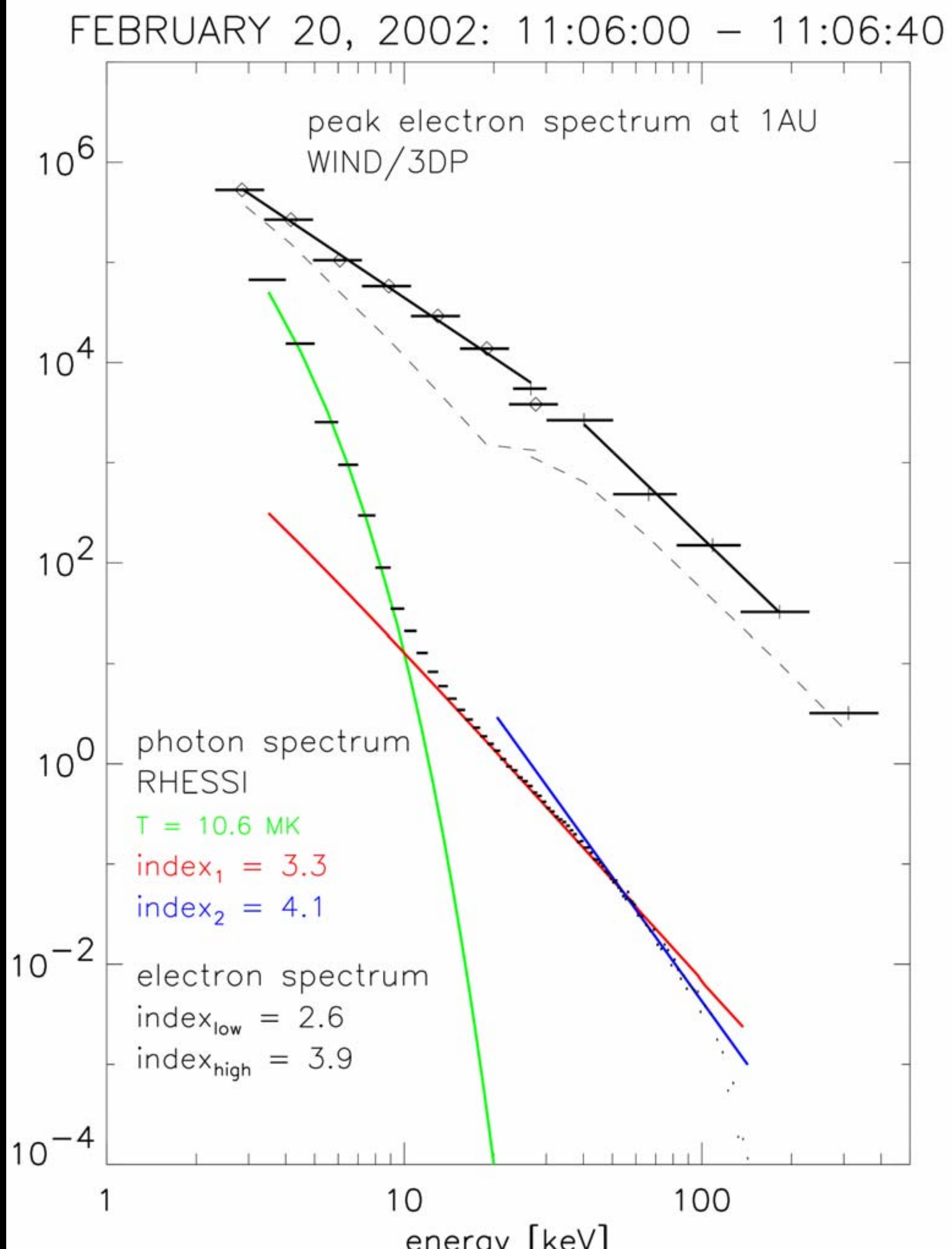


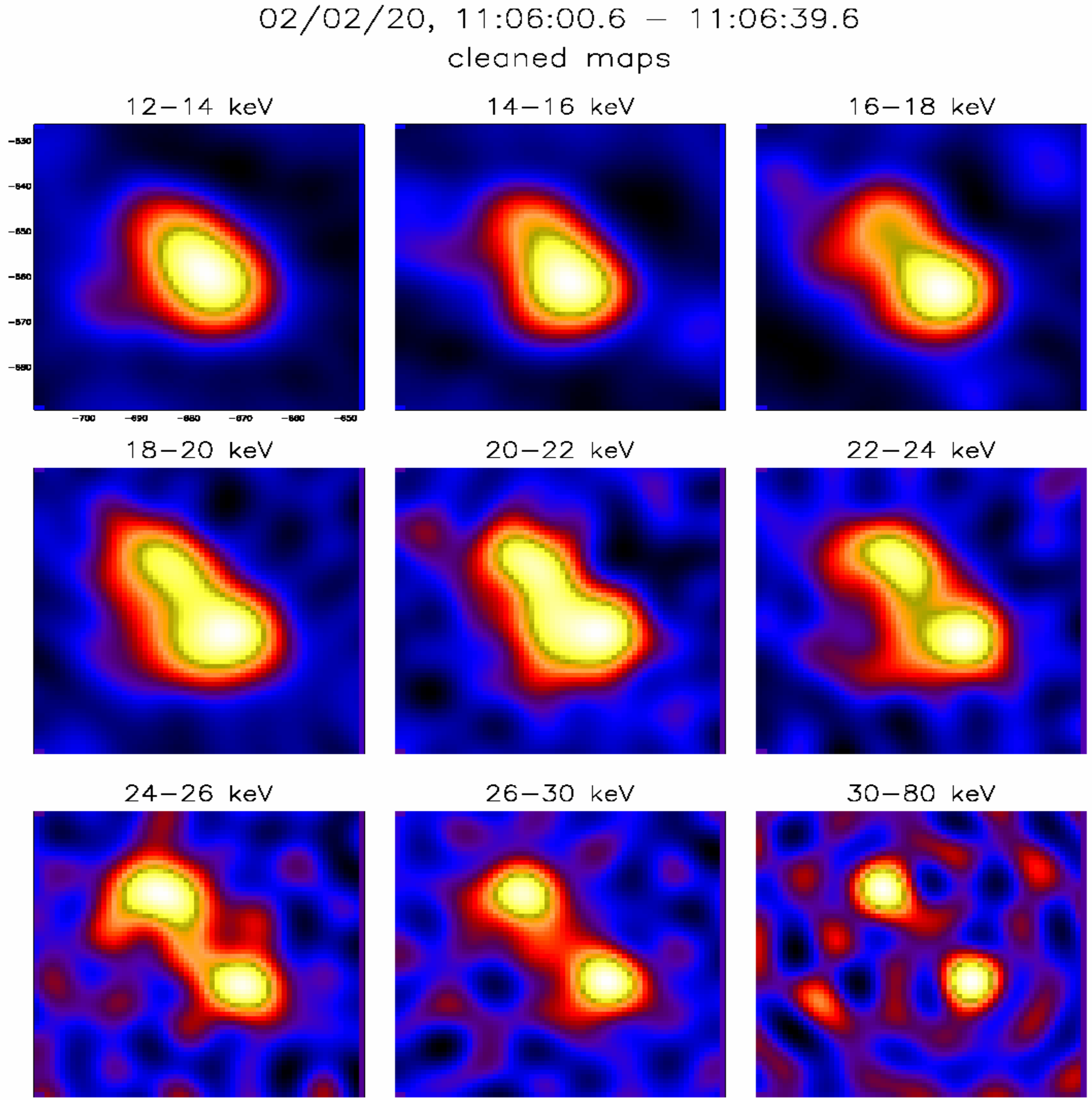
F1309_18.ai

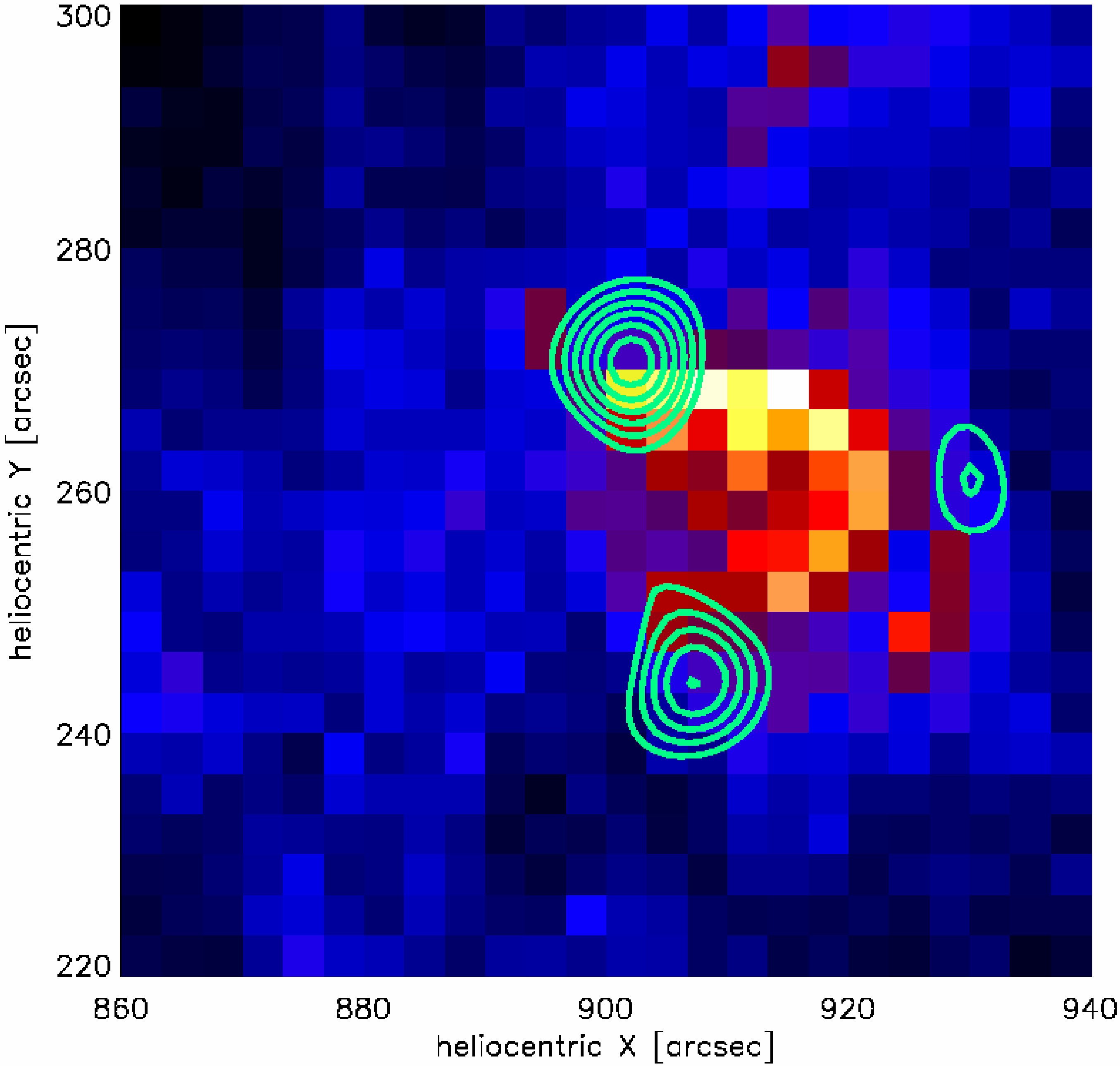

GOES, RHESSI, WIND/WAVES, WIND/3DP
GOES flux [Watt m^-2]
1.6-12.4 keV
3.1-24.8 keV
photon energy [keV]
4000
10
frequency [Hz]
1.32•10^-15
1.84•10^-21
TNR : freq (Hz)
20.735
0.046
electron flux
27 keV
40 keV
66 keV
108 keV
182 keV
310 keV
517 keV
Mon May 13 09:48:14 2002
hhmm
2002 Feb 20
1100
1130
1200
electron release time



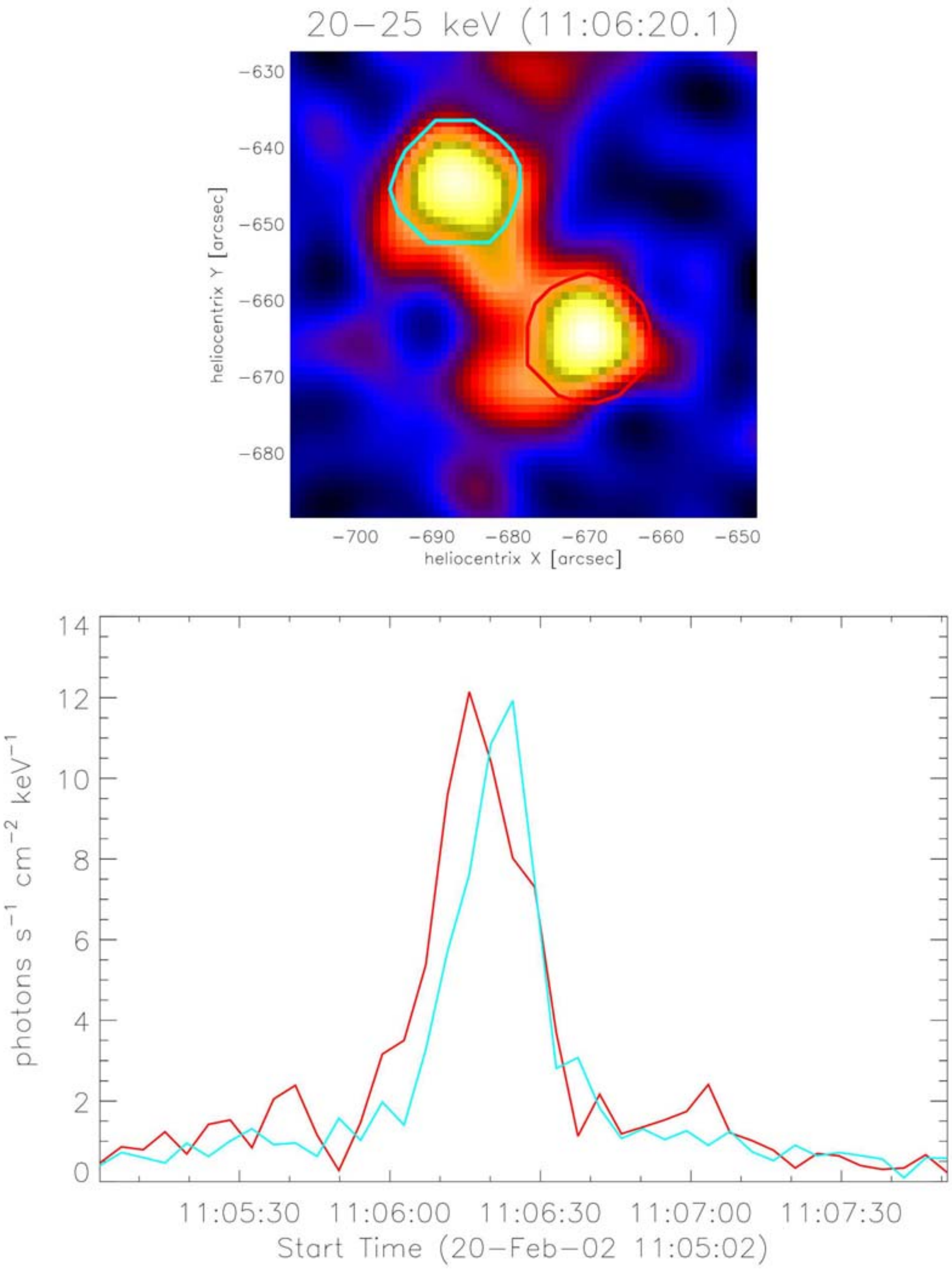
HESSI SPECTRUM
Photons s-1 cm-2 keV-1
10^4
10^2
10^0
10^-2
10^-4
1
10
100
Energy (keV)
10-Apr-2002 20:50
Interval 0
11:06:11.99 - 11:06:24.00
f_vth_bpow parameters: 0.4495, 0.9123, 0.07185, 3.319, 52.00, 4.121

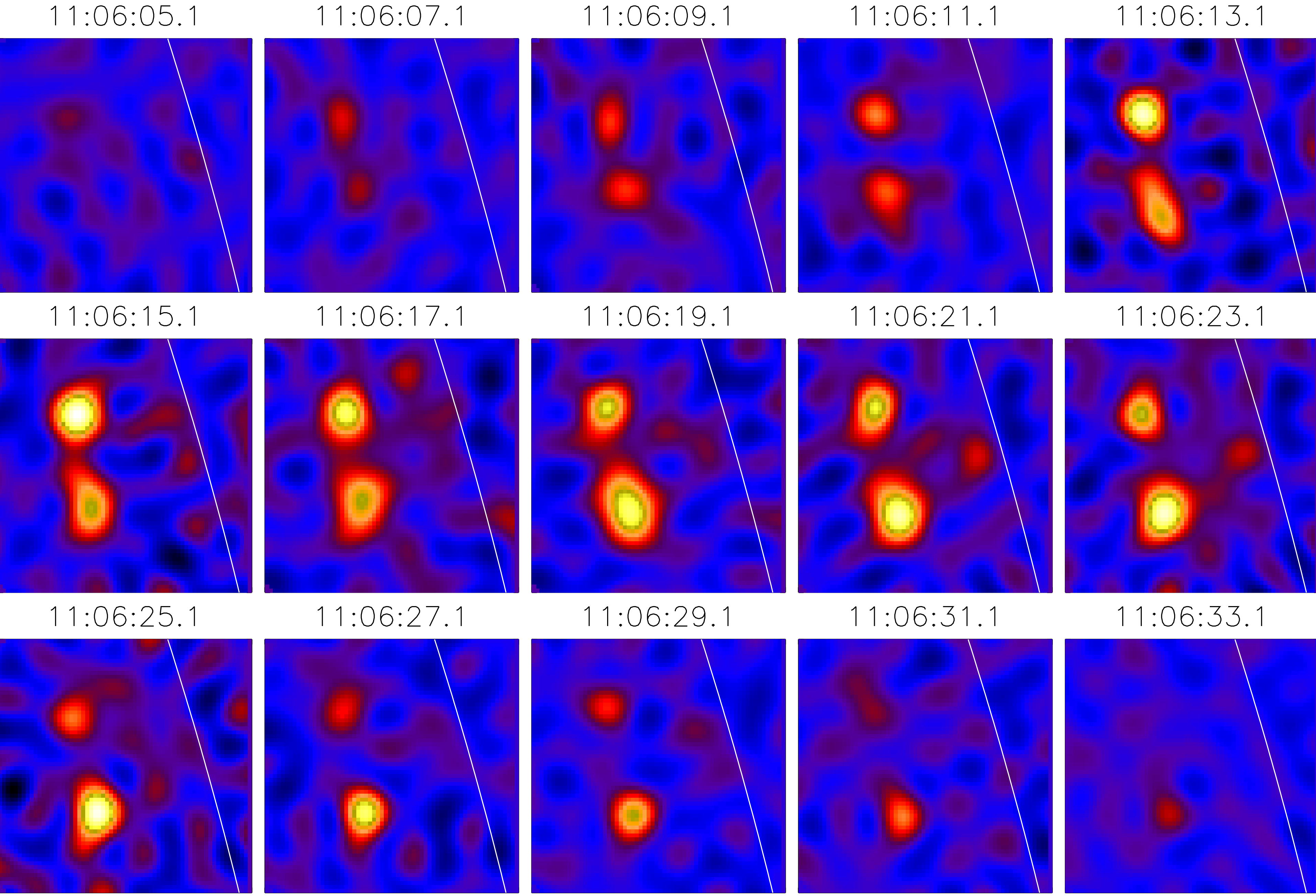

FEBRUARY 20, 2002: 11:06:00 – 11:06:40
peak electron spectrum at 1AU
WIND/3DP
photon spectrum
RHESSI
T = 10.6 MK
index$_1$ = 3.3
index$_2$ = 4.1
electron spectrum
index$_{low}$ = 2.6
index$_{high}$ = 3.9
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
1
10
100
energy [keV]

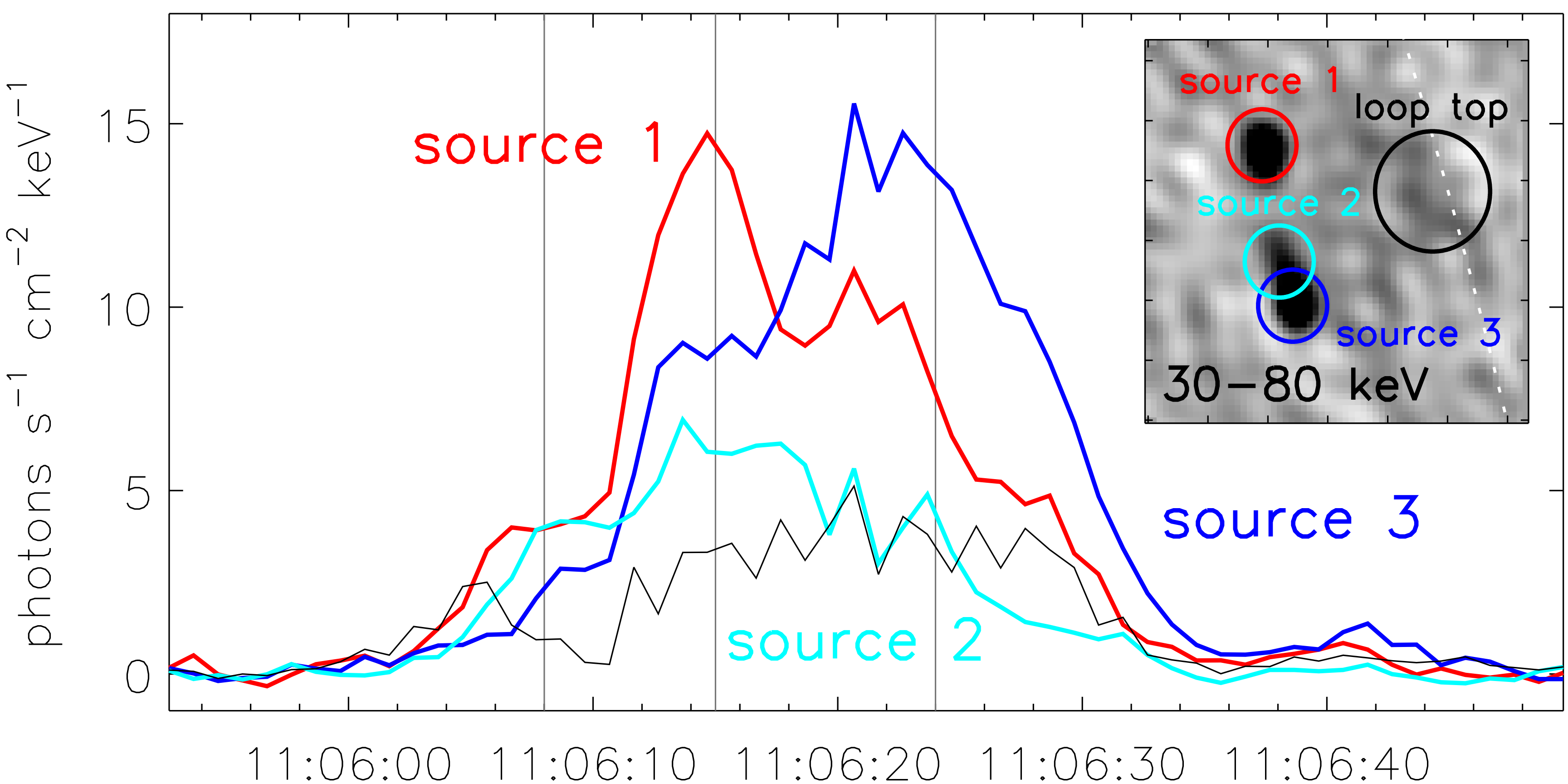

02/02/20, 11:06:00.6 – 11:06:39.6
cleaned maps
12–14 keV
14–16 keV
16–18 keV
18–20 keV
20–22 keV
22–24 keV
24–26 keV
26–30 keV
30–80 keV



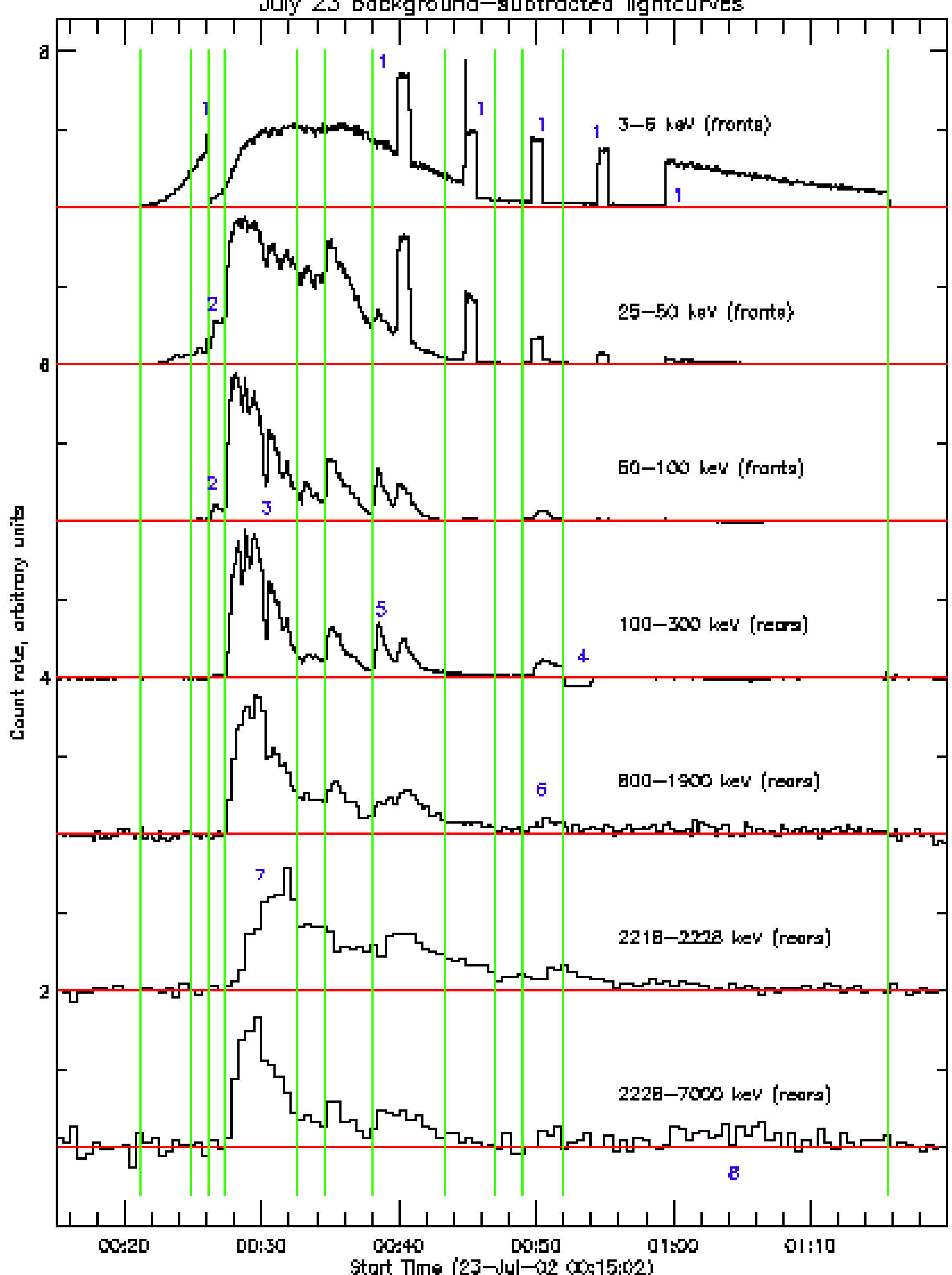
300
280
260
240
220
heliocentric Y [arcsec]
860
880
900
920
940
heliocentric X [arcsec]


20–25 keV (11:06:20.1)
−630
−640
−650
−660
−670
−680
heliocentrix Y [arcsec]
−700
−690
−680
−670
−660
−650
heliocentrix X [arcsec]
14
12
10
8
6
4
2
0
photons s^{-1} cm^{-2} keV^{-1}
11:05:30
11:06:00
11:06:30
11:07:00
11:07:30
Start Time (20–Feb–02 11:05:02)

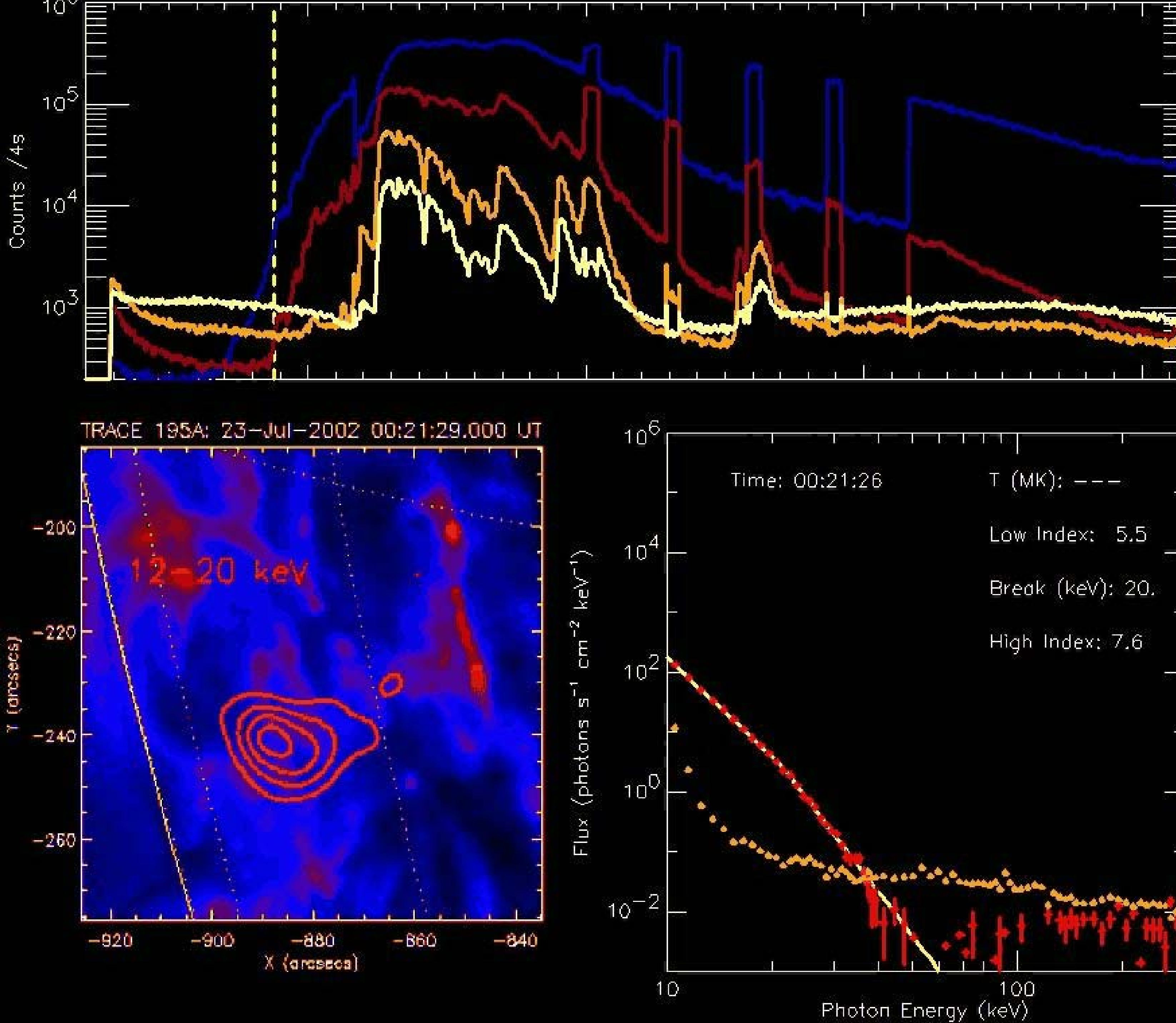

11:06:05.1
11:06:07.1
11:06:09.1
11:06:11.1
11:06:13.1
11:06:15.1
11:06:17.1
11:06:19.1
11:06:21.1
11:06:23.1
11:06:25.1
11:06:27.1
11:06:29.1
11:06:31.1
11:06:33.1



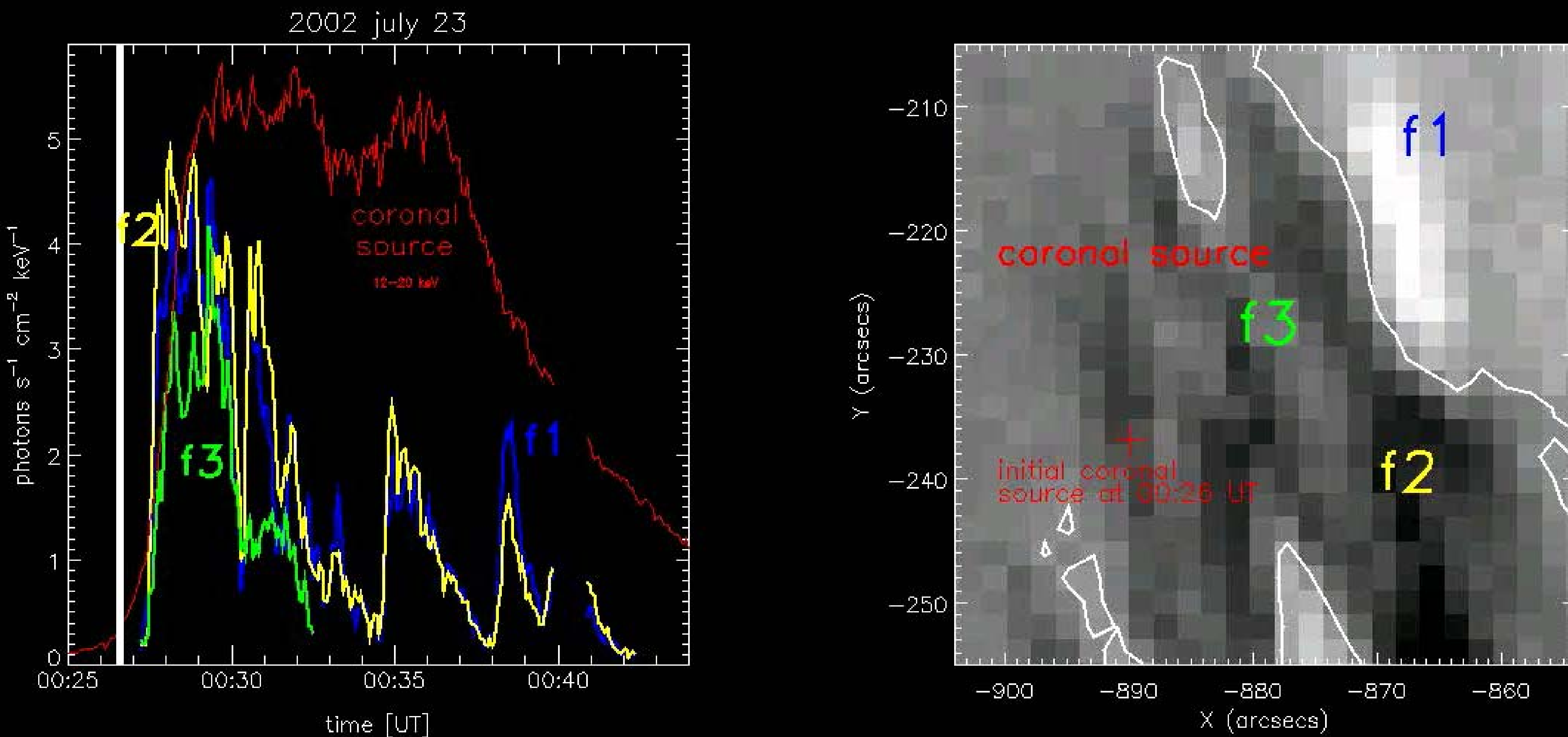
photons s^-1 cm^-2 keV^-1
0
5
10
15
11:06:00
11:06:10
11:06:20
11:06:30
11:06:40
source 1
source 2
source 3
loop top
30-80 keV

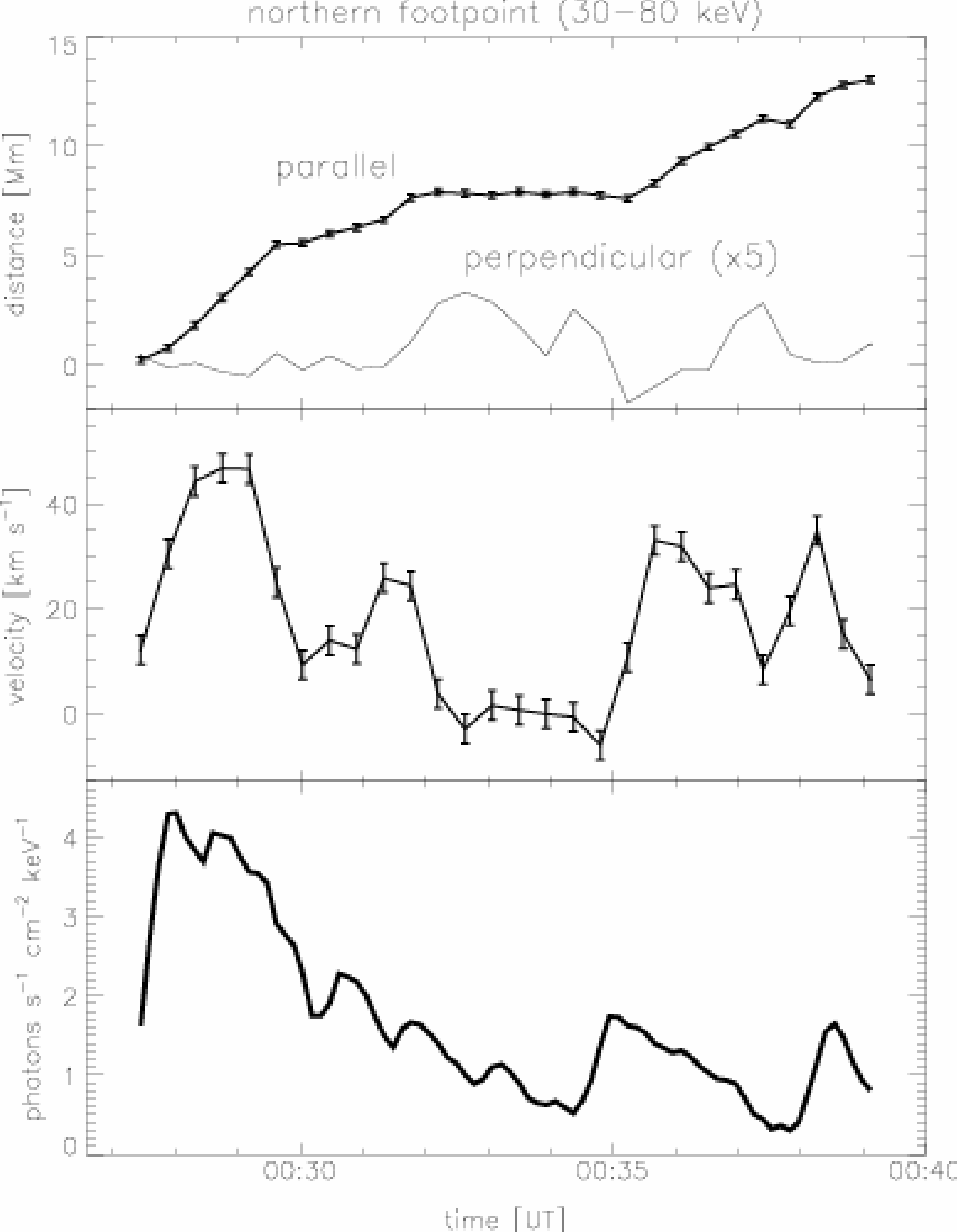


July 23 background-subtracted lightcurves
3-6 keV (fronts)
25-50 keV (fronts)
50-100 keV (fronts)
100-300 keV (rears)
800-1900 keV (rears)
2218-2228 keV (rears)
2228-7000 keV (rears)
Count rate, arbitrary units
Start Time (23-Jul-02 00:15:02)
00:20
00:30
00:40
00:50
01:00
01:10
8
6
4
2
1
2
3
4
5
6
7
8

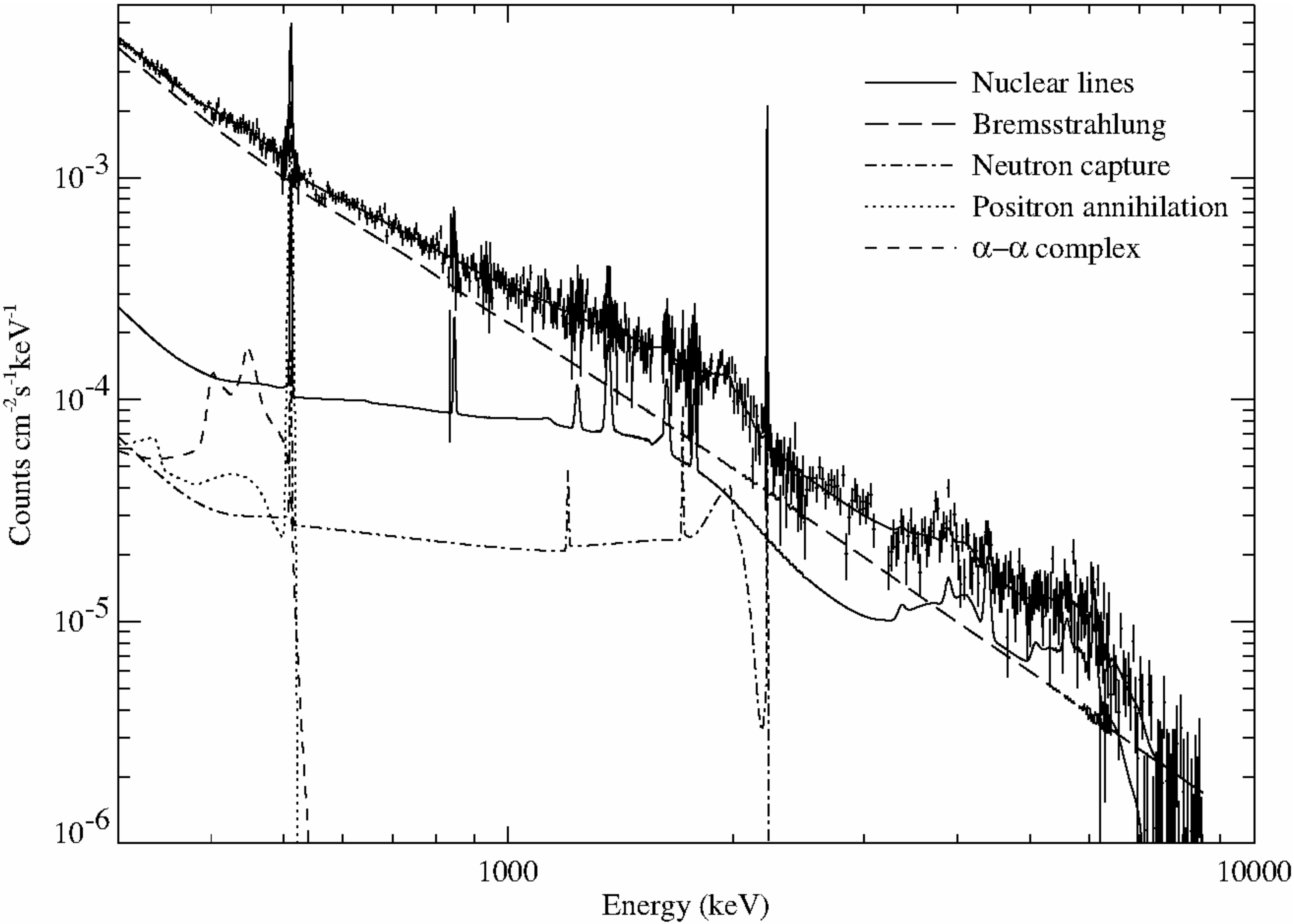


Counts /4s
TRACE 195A: 23-Jul-2002 00:21:29.000 UT
12–20 keV
Y (arcsecs)
X (arcsecs)
Time: 00:21:26
T (MK): ---
Low Index: 5.5
Break (keV): 20.
High Index: 7.6
Flux (photons s⁻¹ cm⁻² keV⁻¹)
Photon Energy (keV)

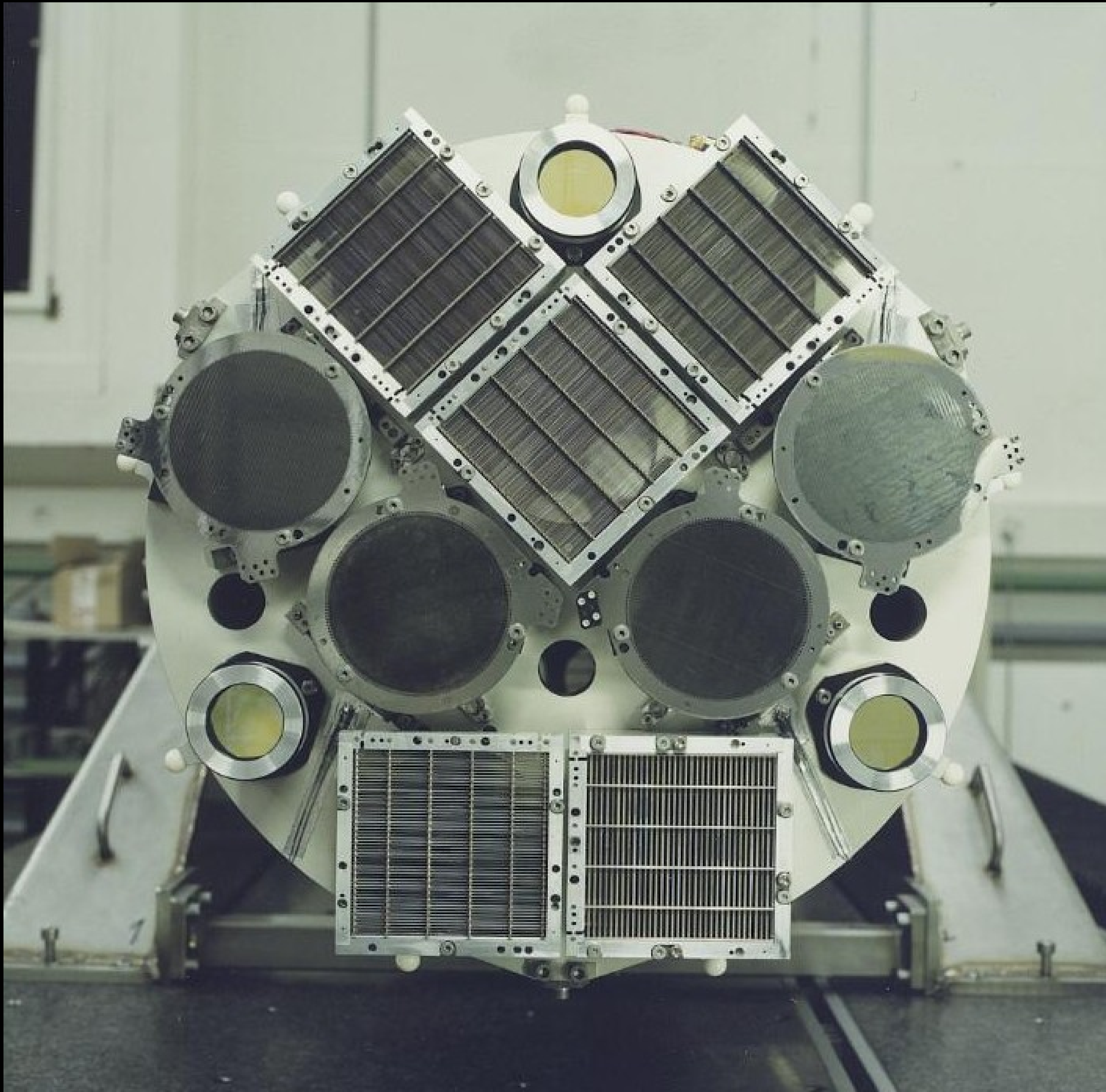

2002 july 23
photons s^-1 cm^-2 keV^-1
time [UT]
00:25
00:30
00:35
00:40
coronal
source
12-20 keV
f2
f3
f1
Y (arcsecs)
X (arcsecs)
-210
-220
-230
-240
-250
-900
-890
-880
-870
-860
coronal source
f1
f3
f2
initial coronal
source at 00:26 UT

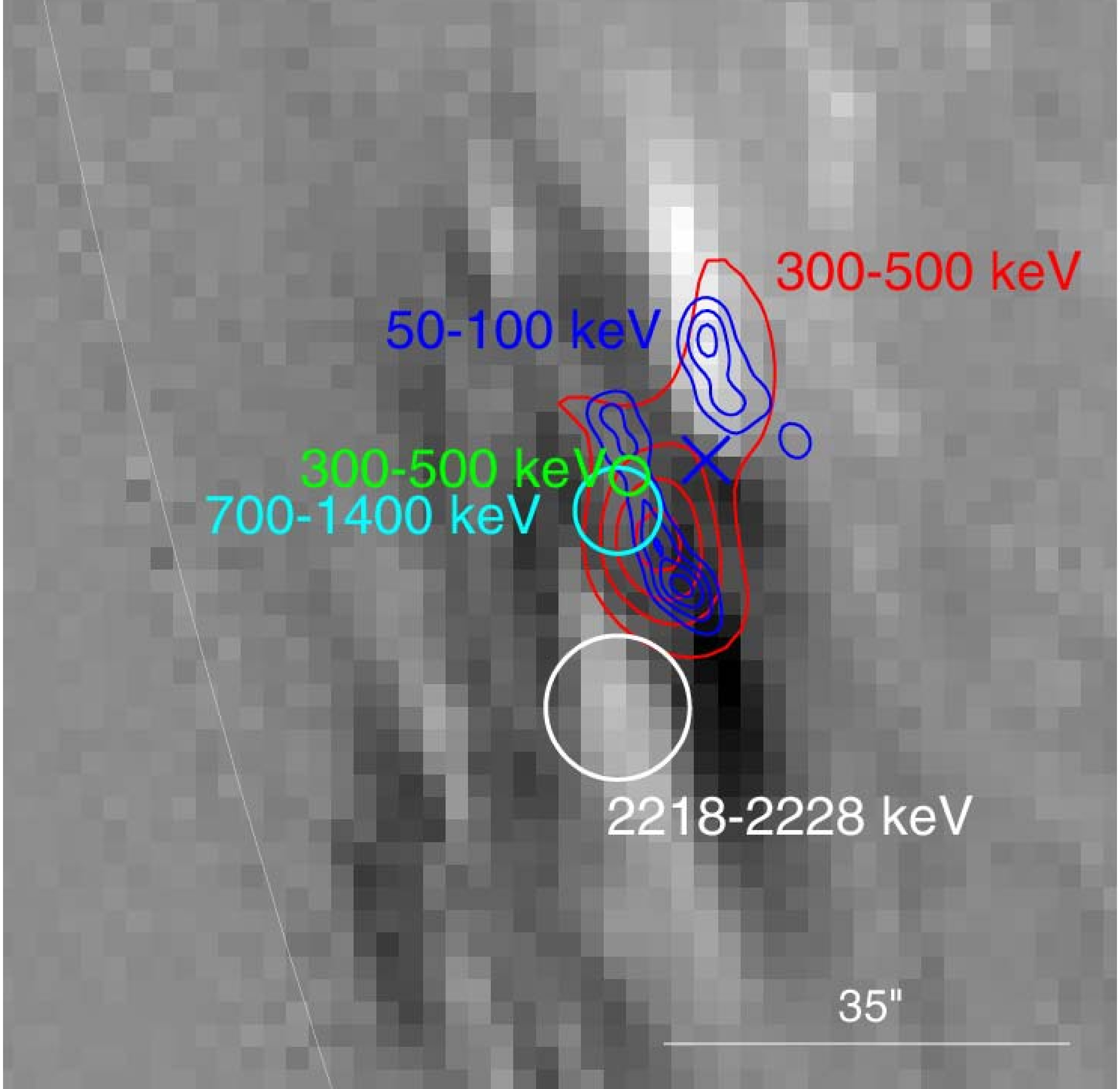


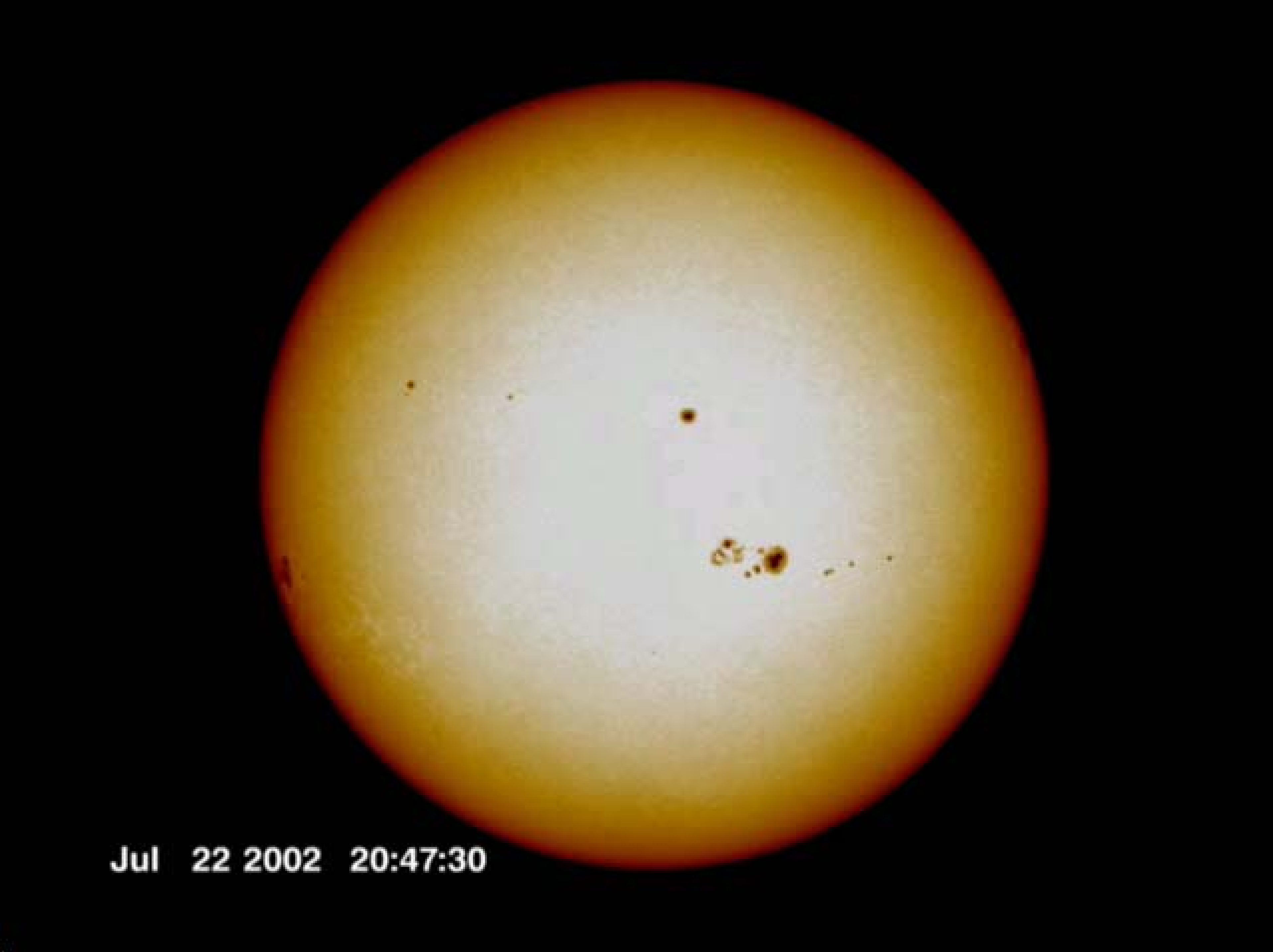
northern footpoint (30–80 keV)
parallel
perpendicular (x5)
distance [Mm]
velocity [km s^{-1}]
photons s^{-1} cm^{-2} keV^{-1}
00:30
00:35
00:40
time [UT]

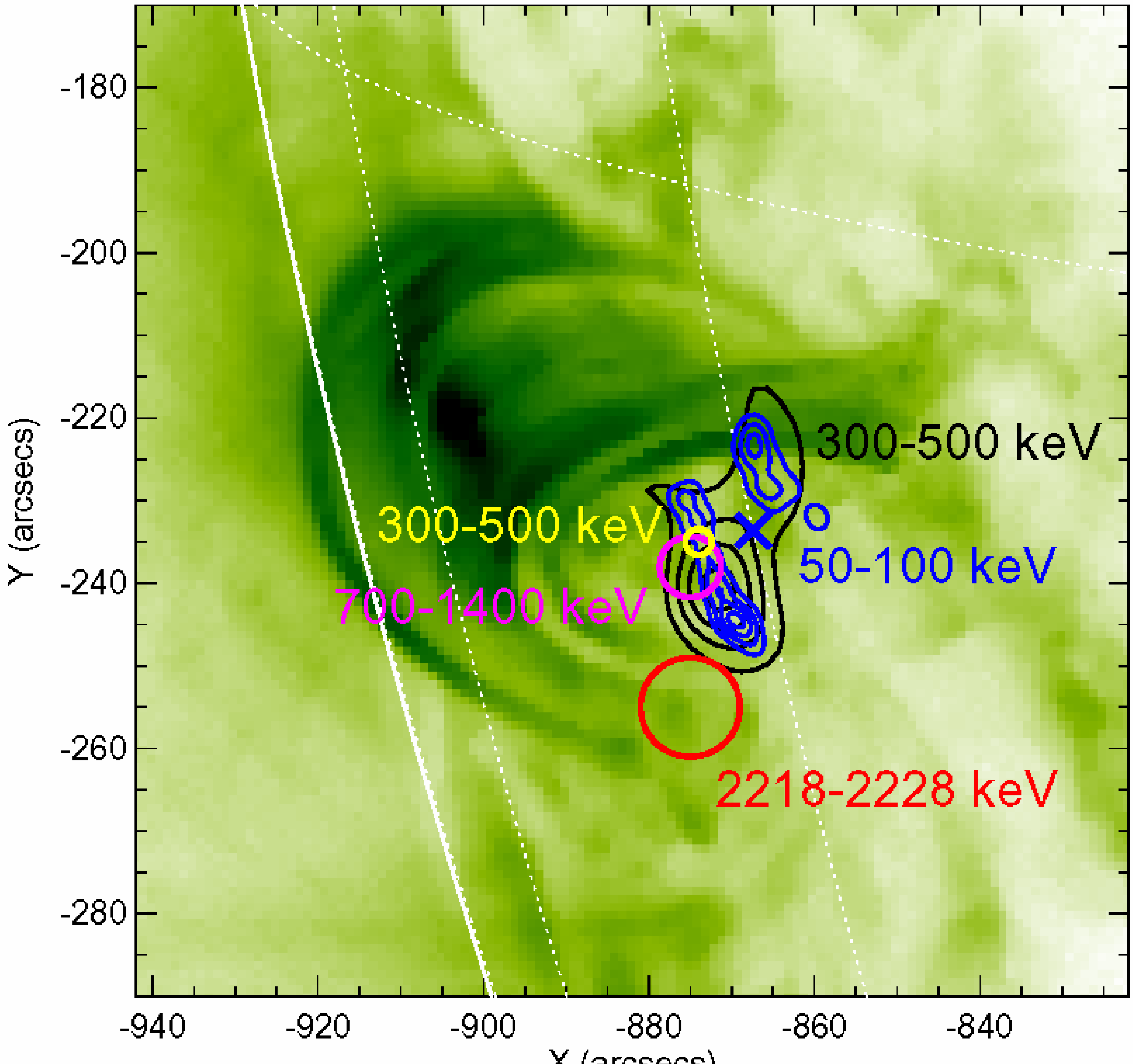


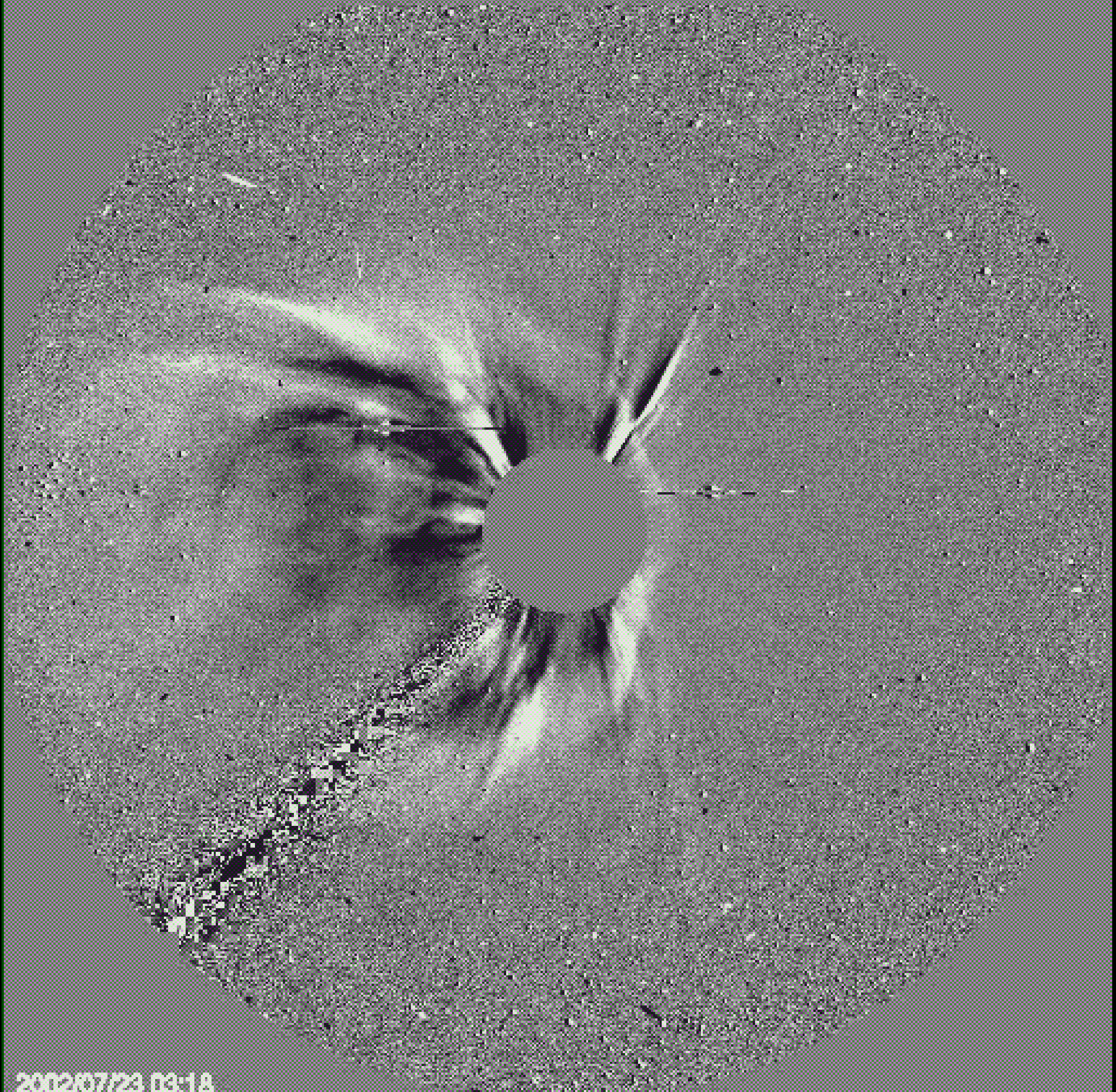
Nuclear lines
Bremsstrahlung
Neutron capture
Positron annihilation
α–α complex
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Counts cm^{-2}s^{-1}keV^{-1}
1000
10000
Energy (keV)




300-500 keV
50-100 keV
300-500 keV
700-1400 keV
2218-2228 keV
35"


Jul 22 2002 20:47:30


300-500 keV
300-500 keV
50-100 keV
700-1400 keV
2218-2228 keV
Y (arcsecs)
X (arcsecs)
-180
-200
-220
-240
-260
-280
-940
-920
-900
-880
-860
-840


2002/07/23 03:18

Solar Energetic Particle (SEP) events observed in the Interplanetary Medium (IPM):

* ***<u>Large (L)SEP events</u>* *(~tens per year at solar maximum)***

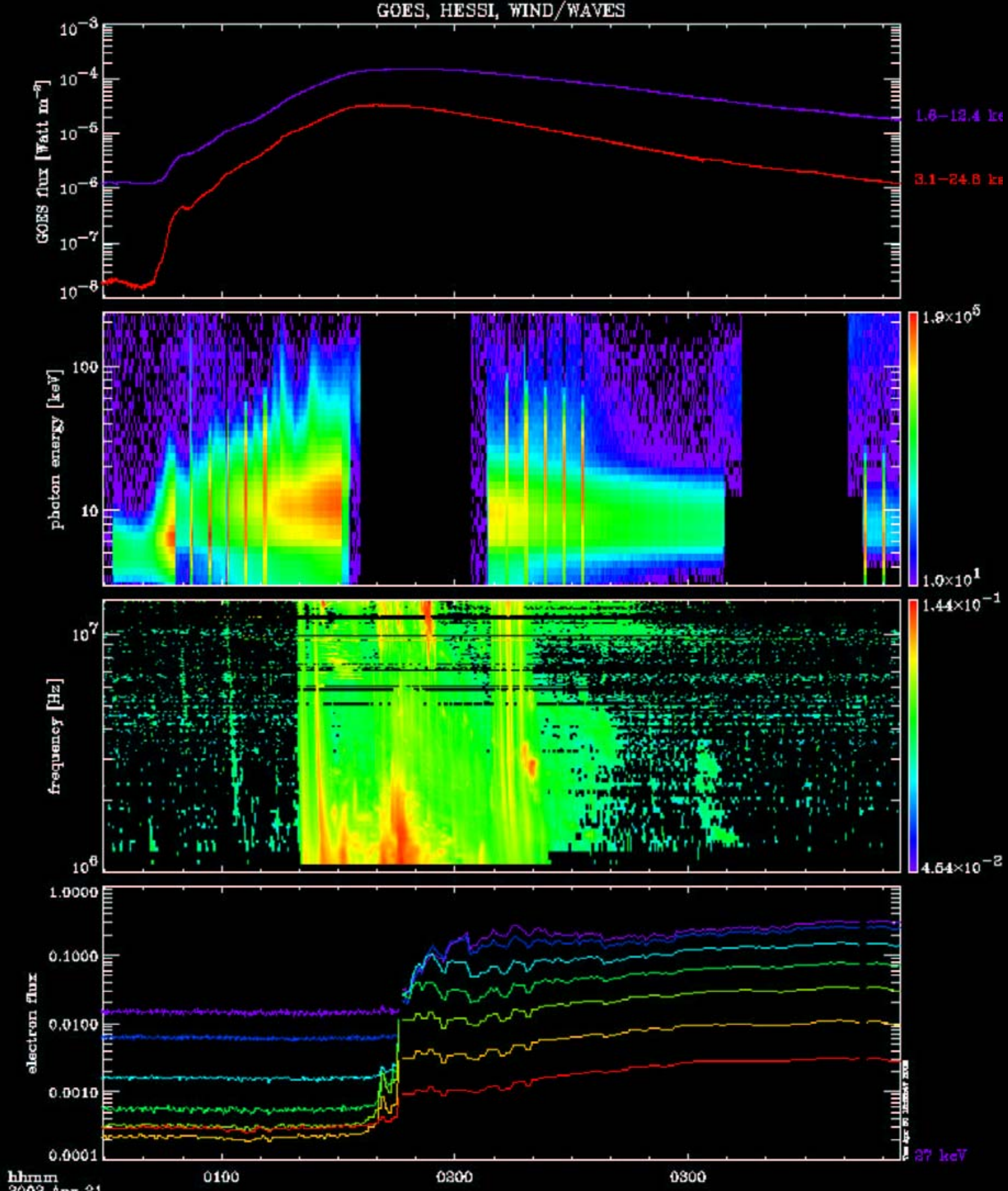
- dominated by >10 MeV protons
normal coronal composition and charge states

- associated with fast Coronal Mass Ejections (CMEs)
large flares (sometimes missing)
gradual soft X-ray bursts

* ***<u>Electron - ^{3}He-rich SEP events</u>* *(~10^{3}s per year at solar maximum)***

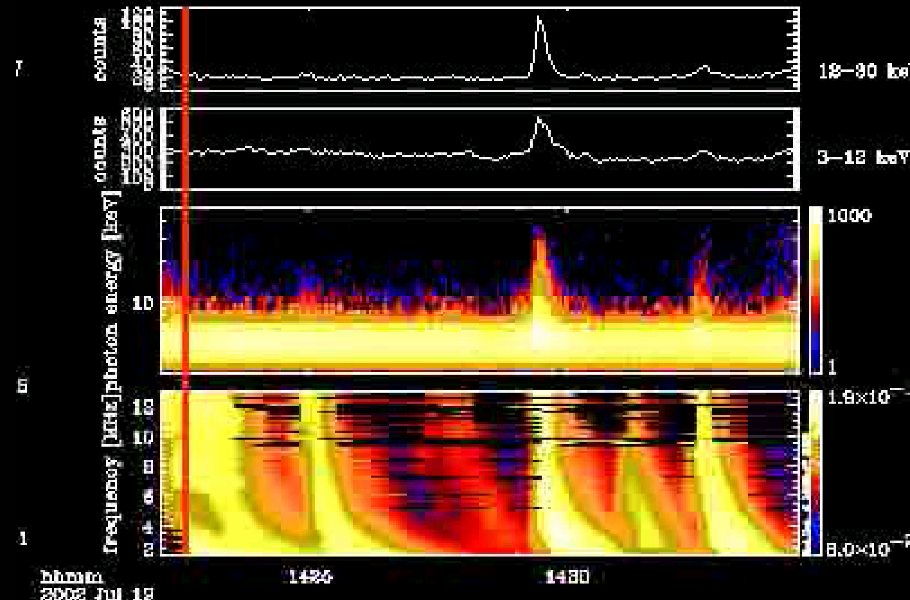
- dominated by ~ 1-100 keV electrons and ~ MeV/nuc ^{3}He
enhanced Fe, Mg, Si, S; high charge states

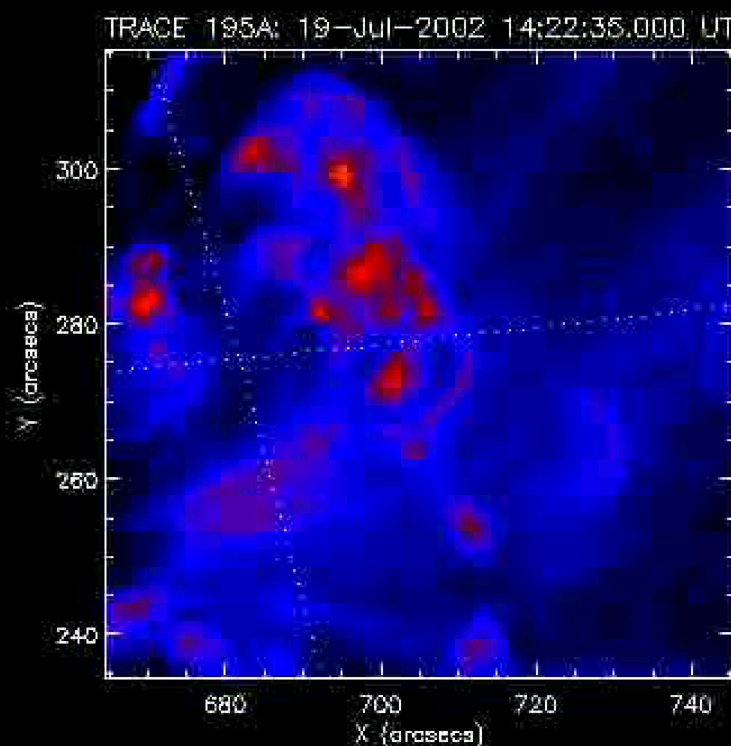
- associated with small flares/coronal microflares
Type III radio bursts
impulsive soft X-ray bursts

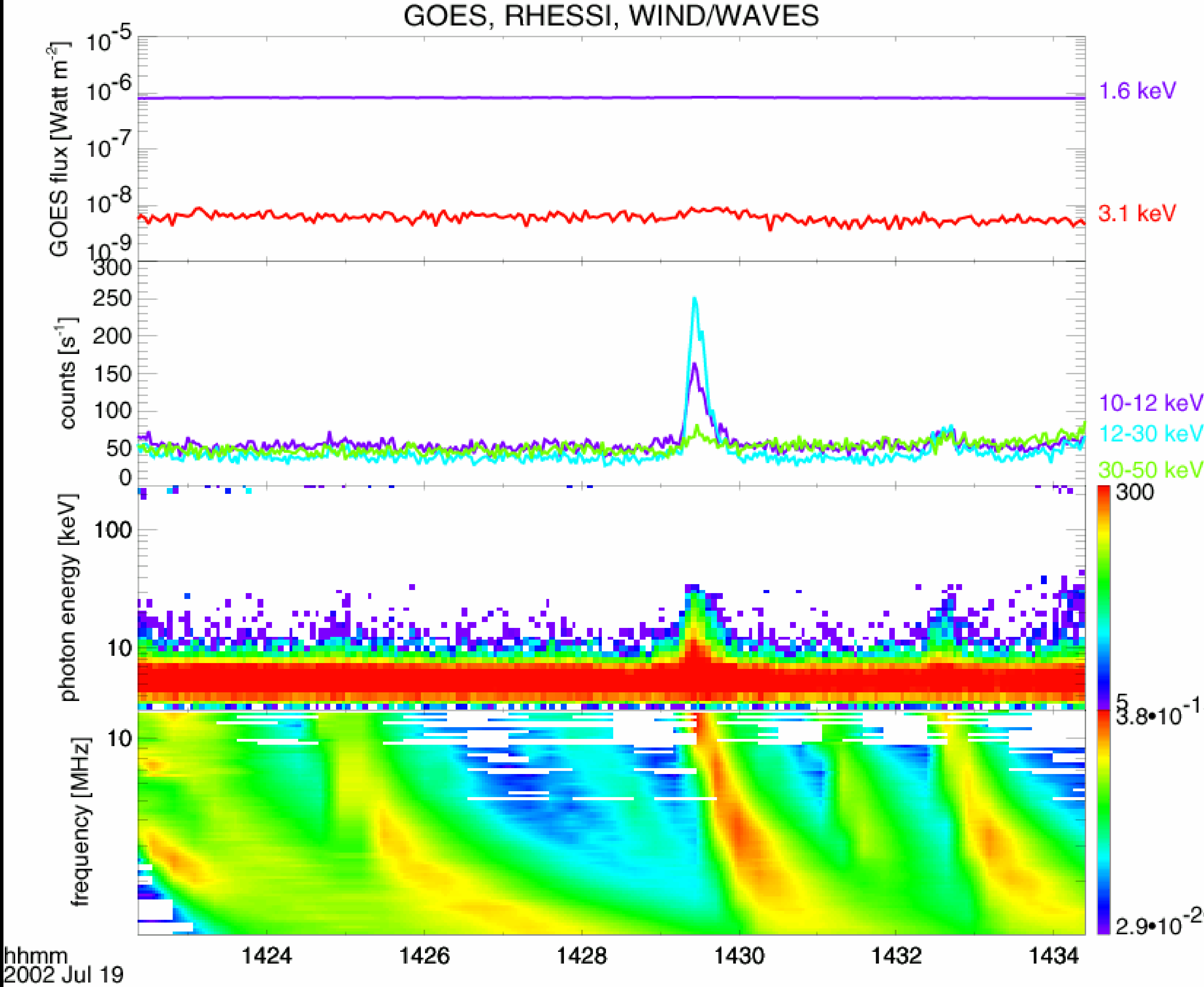


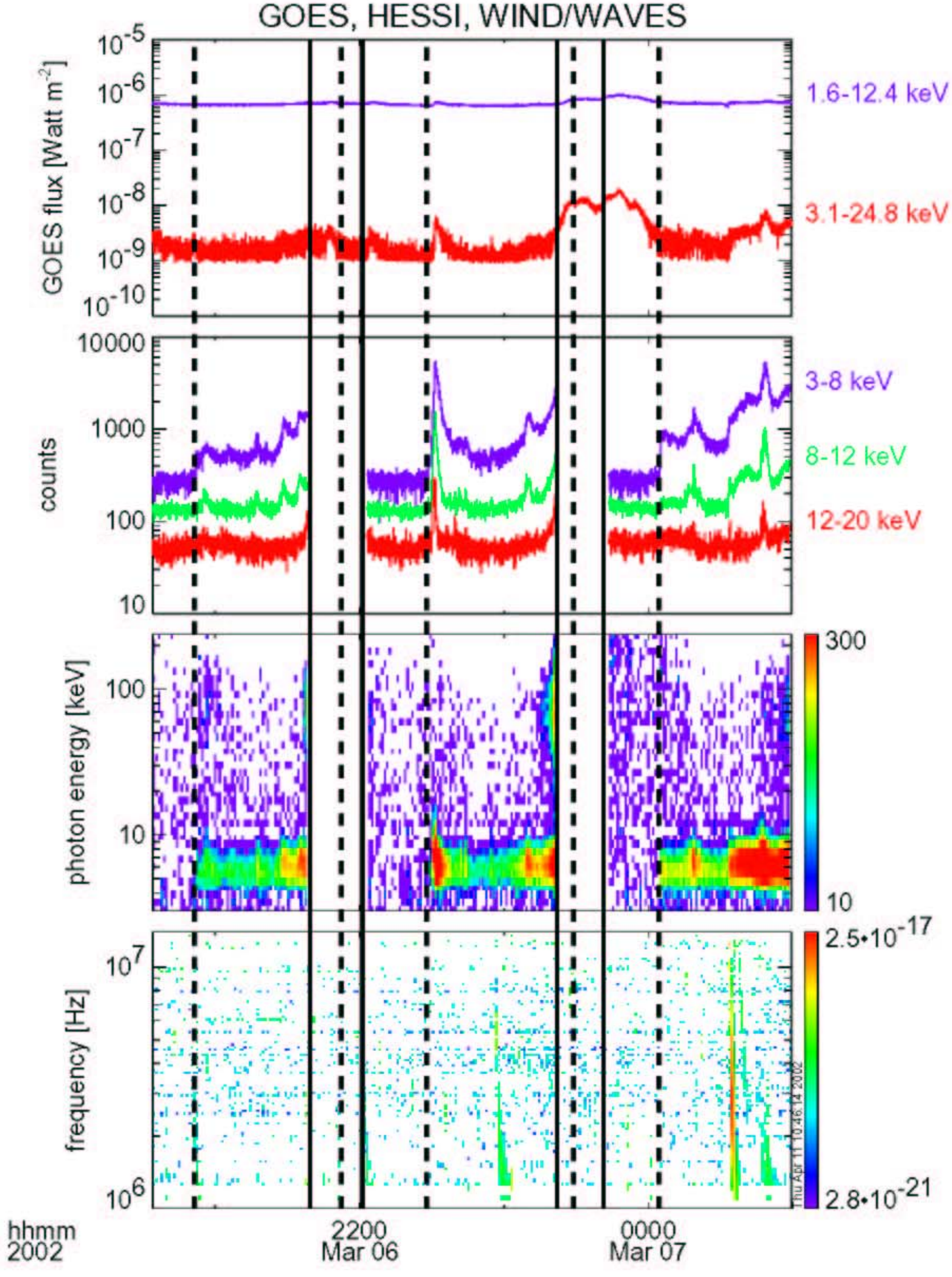
GOES, HESSI, WIND/WAVES
GOES flux [Watt m^{-2}]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1.6–12.4 ke
3.1–24.8 ke
photon energy [keV]
100
10
1.9×10^{5}
1.0×10^{1}
frequency [Hz]
10^{7}
10^{6}
1.44×10^{-1}
4.64×10^{-2}
electron flux
1.0000
0.1000
0.0100
0.0010
0.0001
27 keV
hhmm
2002 Apr 21
0100
0200
0300

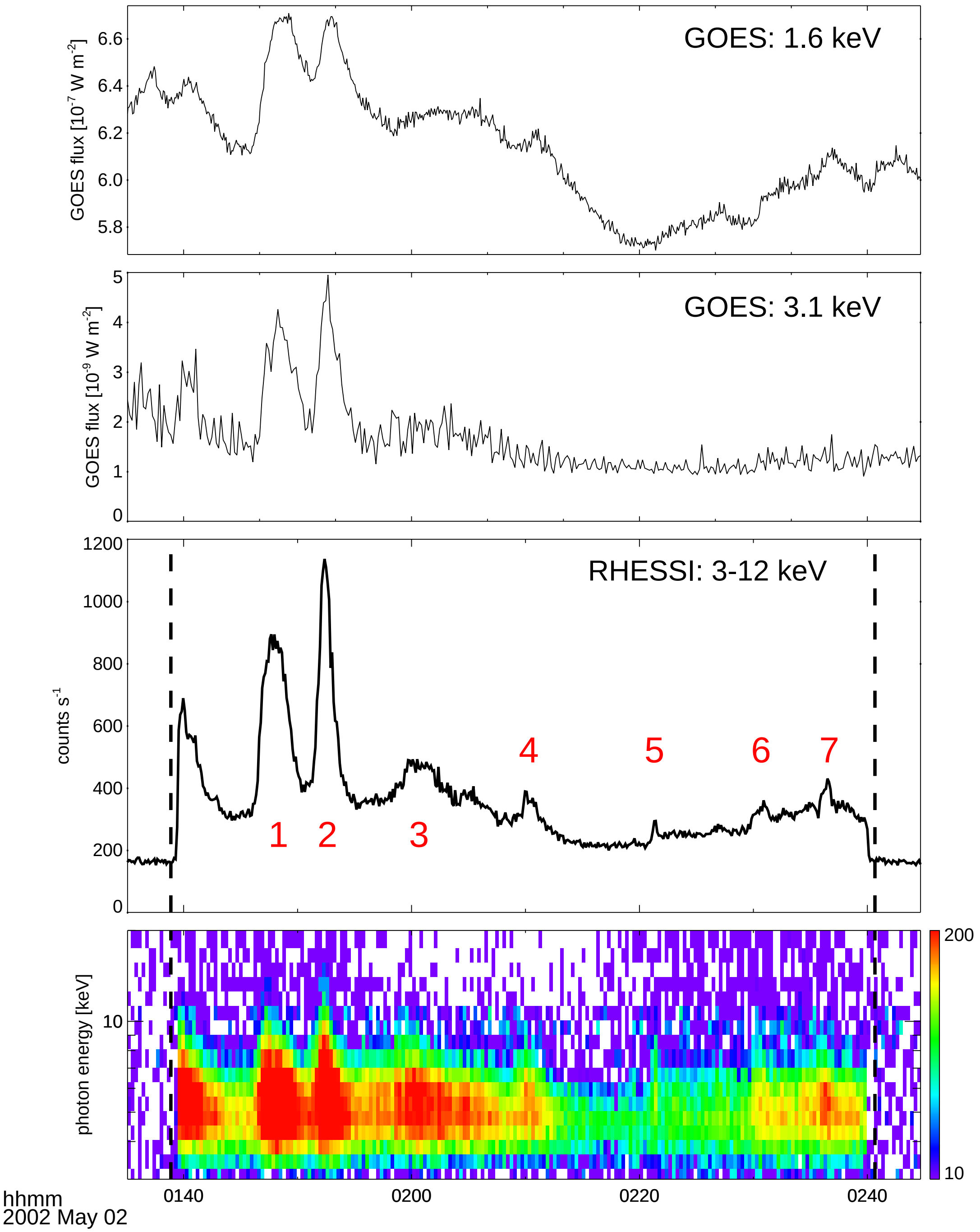

Apr 17 2002 23:59:32


counts
counts
3-12 keV
photon energy [keV]
1000
hhmm

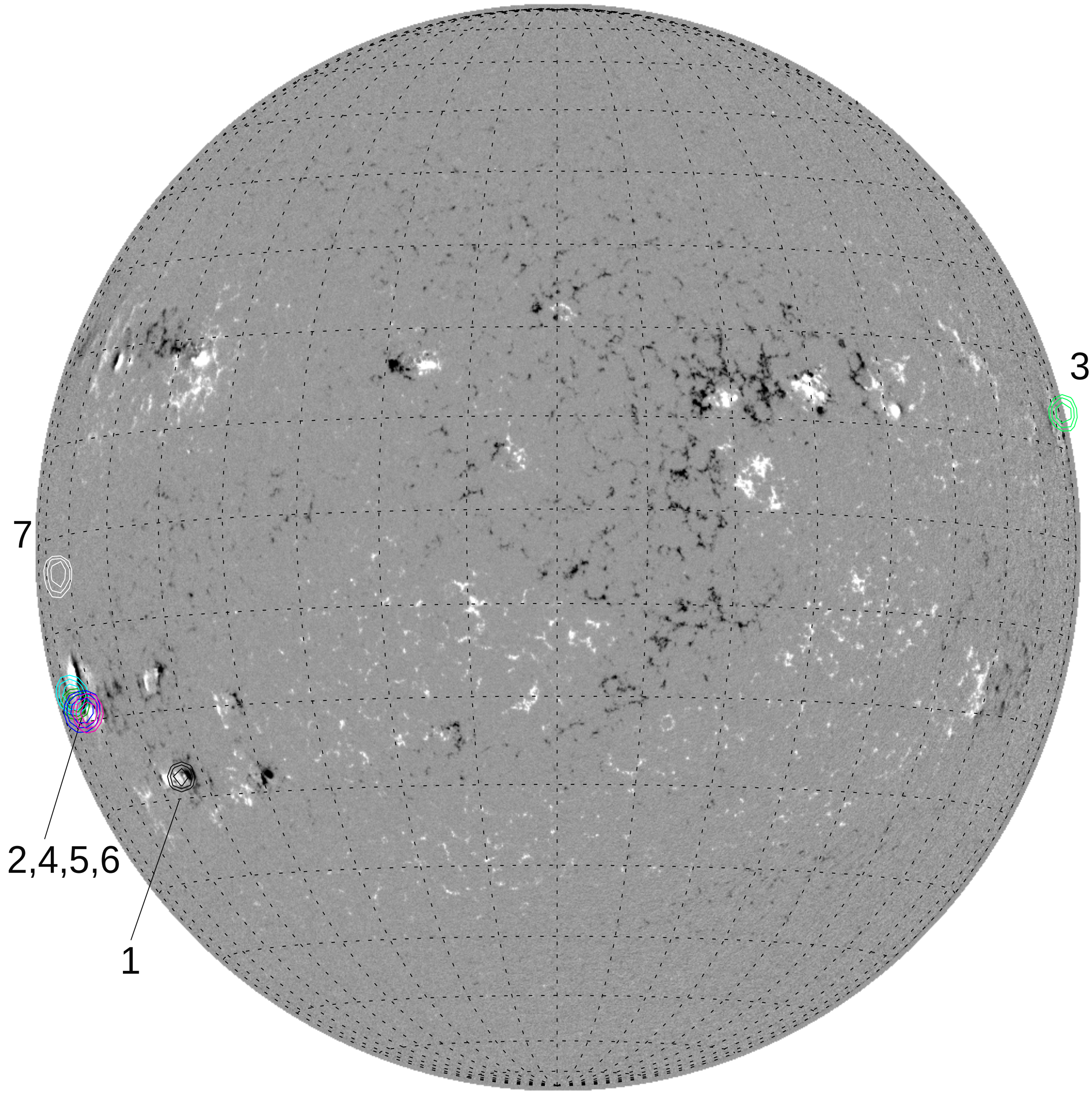

TRACE 195A: 19-Jul-2002 14:22:35.000 UT
Y (arcsecs)
X (arcsecs)
300
280
260
240
680
700
720
740

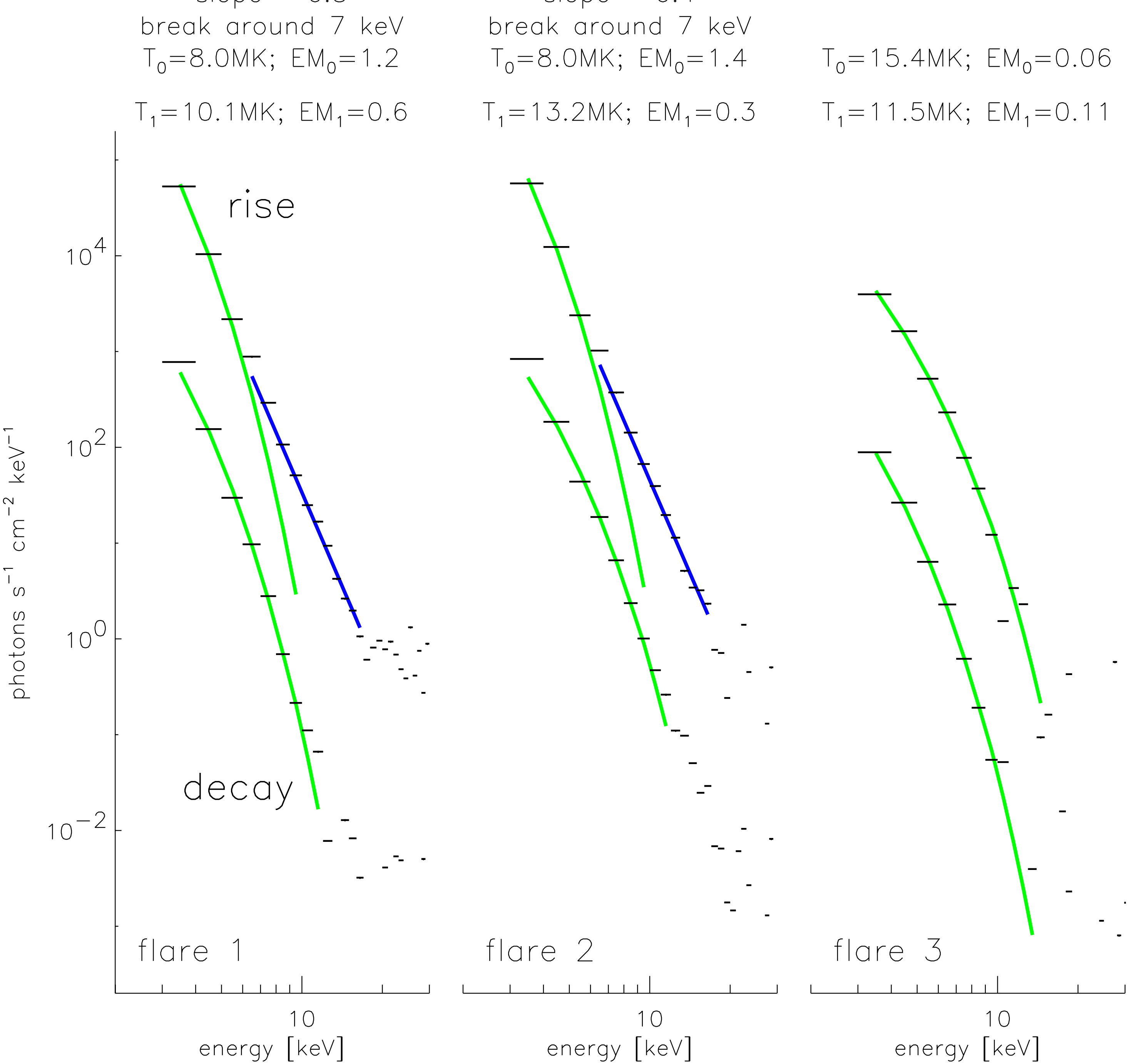

GOES, RHESSI, WIND/WAVES
GOES flux [Watt m^{-2}]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
1.6 keV
3.1 keV
counts [s^{-1}]
300
250
200
150
100
50
0
10-12 keV
12-30 keV
30-50 keV
photon energy [keV]
100
10
300
5
frequency [MHz]
10
$3.8 \cdot 10^{-15}$
$2.9 \cdot 10^{-20}$
hhmm
2002 Jul 19
1424
1426
1428
1430
1432
1434


GOES, HESSI, WIND/WAVES
GOES flux [Watt m^{-2}]
1.6-12.4 keV
3.1-24.8 keV
counts
3-8 keV
8-12 keV
12-20 keV
photon energy [keV]
300
10
frequency [Hz]
$2.5 \cdot 10^{-17}$
$2.8 \cdot 10^{-21}$
hhmm
2002
2200
Mar 06
0000
Mar 07



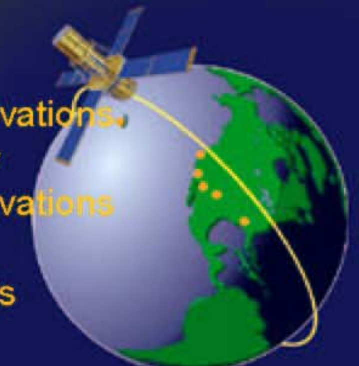
GOES: 1.6 keV
GOES flux [10^-7 W m^-2]
6.6
6.4
6.2
6.0
5.8
GOES: 3.1 keV
GOES flux [10^-9 W m^-2]
5
4
3
2
1
0
RHESSI: 3-12 keV
counts s^-1
1200
1000
800
600
400
200
0
1
2
3
4
5
6
7
photon energy [keV]
10
200
10
0140
0200
0220
0240
hhmm
2002 May 02


3
7
2,4,5,6
1


break around 7 keV
T0=8.0MK; EM0=1.2
T1=10.1MK; EM1=0.6
break around 7 keV
T0=8.0MK; EM0=1.4
T1=13.2MK; EM1=0.3
T0=15.4MK; EM0=0.06
T1=11.5MK; EM1=0.11
rise
decay
photons s−1 cm−2 keV−1
10^4
10^2
10^0
10^−2
flare 1
flare 2
flare 3
10
energy [keV]
10
energy [keV]
10
energy [keV]

HESSI PI and Co-Is

Robert Lin	University of California, Berkeley	PI
Gordon Hurford	University of California, Berkeley	Imaging Scientist
Norman Madden	LBNL, Berkeley	Germanium Detectors
Brian Dennis	GSFC/682	Mission Scientist
Carol Crannell	GSFC/682	Education & Outreach
Gordon Holman	GSFC/682	Flare Theory
Reuven Ramaty	GSFC/661	Flare Theory
Tycho von Rosenvinge	GSFC/661	ACE Collaboration
Alex Zehnder	Paul Scherrer Inst. Switzerland	Telescope design and fabrication
Frank van Beek	Driebergen, The Netherlands	Grids and Imaging
Patricia Bornmann	NOAA	GOES Collaboration
Richard Canfield	Montana State University	Ground-based Observations
Gordon Emslie	Univ. of Alabama, Huntsville	Flare Theory
Hugh Hudson	Solar Physics Research Corp.	Imaging
Arnold Benz	Inst. of Astronomy, Zurich, Switzerland	Radio Observations
John Brown	Univ. of Glasgow, Scotland	Flare Theory
Shinzo Enome	NAO, Japan	Radio Observations
Takeo Kosugi	NAO, Japan	Imaging
Nicole Vilmer	Observatoire de Paris, Meudon, France	Data Analysis



A1309.012

HESSI Associated Scientists

University of California, Berkeley

David Smith	Spectrometer Scientist
Jim McTiernan	MOC/SOC Scientist
Isabel Hawkins	Education & Outreach
Said Slassi-Sennou	Spectrometer
Calibration	
Andre Csillaghy	Software
George Fisher	Flare Theory
Chris Johns-Krull	Modeling

GSFC

Richard Schwartz	Data Analysis
Software	
Larry Orwig	Grid Characterization
Dominic Zarro	Complementary Data

University of Maryland

Ed Schmahl	Imaging Software

Lockheed-Martin

Markus Aschwanden	Timing Software

A1309.012

Thanks also to:

Researchers

Sam Krucker, UCB

Gerry Share, NRL

Ron Murphy, NRL

Grad Students

Steven Christe, UCB

Martin Fivian, ETHZ

Amir Caspi, UCB

Albert Shih UCB

Linhui Sui, Catholic U

RHESSI project team at **UCB, Goddard Space Flight Center, and the Paul Scherrer Institute (Switzerland)**

Gamma Ray Bursts Get Magnetic

Cherished notions about gamma ray bursts (GRBs), the brightest explosions in the universe, have been upended by an unlikely source: a satellite that studies the sun with nine solid state detectors, each just a bit bigger than a soda can. Highly organized radiation streaming from the heart of a recent GRB, picked up by the detectors as they aimed at the sun, strongly suggests that the burst consisted almost entirely of electromagnetic energy rather than fast-moving matter as most theorists have assumed.

Astrophysicists think GRBs arise when the cores of giant stars collapse into spinning black holes within about 10 seconds. According to computer models, a thick torus of whirling gas plunges into the black hole while jets blast out of the top and bottom of the torus, where the material is less dense. If a jet points toward Earth, we see a blast of gamma rays; otherwise, the event looks like a supernova. These models have not included strong magnetic fields, which are extremely difficult to simulate. However, no observations had shown that magnetic fields played a major role in controlling the outbursts of energy from GRBs.

That changed on 6 December 2002, when a burst popped off close to the sun's position on the sky—too close for most telescopes to monitor. However, the gamma rays triggered nearly 100,000 electronic blips in the germanium detectors of the Ramaty High Energy Solar Spectroscopic Imager (RHESSI), a NASA satellite that studies flares on the sun. Some gamma rays scattered from one detector into an adjacent one before being absorbed. By tracing the patterns of this scattering, the RHESSI team found that the gamma rays were almost completely polarized, or aligned with their electric fields in the same direction.

The best explanation is that strong magnetic fields—perhaps more powerful than any others in the universe—ordered the burst's energy, says physicist Steven Boggs of the University of California, Berkeley, who reported the work at the meeting and in the 22 May issue of *Nature*. Without such fields, the gamma rays would have sprayed into space with random orientations. No other instruments had ever seen polarization at gamma ray energies, says Boggs, who called it a "milestone" for the field. "RHESSI was not designed for this, but we knew that if we got lucky with a bright burst nearly on axis [of the detectors], we'd see it," he added.

Theorists at the meeting, who had heard rumors of RHESSI's feat for months, were thrilled. "This is absolutely an astounding result," says astrophysicist Donald Lamb of the University of Chicago. "It's a slam dunk that magnetic fields are dominant." Lamb suspects that a jet of charged particles ejected from the region near the black hole could not stay organized enough to produce such strong alignment. Rather, he says, most energy from GRBs may consist of electromagnetic radiation.

Physicist Maxim Lyutikov of McGill University in Montreal, Quebec, and colleagues reached a similar conclusion in a recent online paper (arxiv.org/abs/astro-ph/0305410). In their view, GRBs are particle-free "cold fireballs," launched from an ultramagnetic and furiously spinning neutron star rather than from a black hole.

Watch for more GRB news soon. A forthcoming analysis of energy patterns from dozens of bursts by Lamb and coworkers, described at the meeting, suggests that magnetic fields confine the jets to needlelike cones just half an angular degree wide—far narrower than theorists have thought.

–ROBERT IRION

A18 THE NEW YORK TIMES NATIONAL THURSDAY, MAY 29, 2003

Biggest Blast in Cosmos, Reveals Its Dark Heart

By JOHN NOBLE WILFORD

NASHVILLE, May 28 — While taking X-ray pictures of flares from the Sun in December, a scientific spacecraft happened to detect a tremendous blast of gamma rays from several billion light-years away. The observation, astronomers say, showed the driving force behind what appear to be the most powerful explosions in the universe.

In a report here today at a meeting of the American Astronomical Society, researchers from the University of California at Berkeley said the coherence and alignment, the polarization, of the gamma radiation implied that the tremendous burst of energy originated from a region of highly structured magnetic fields.

The large-scale field, the scientists said, was being generated by the rapid rotation of the extremely dense core object, a black hole or a neutron star, remaining after the explosion of a huge star.

The polarization of the high-energy radiation from the explosion, Dr. Steven E. Boggs of Berkeley said, "is telling us that the magnetic fields themselves are acting as the dyna-

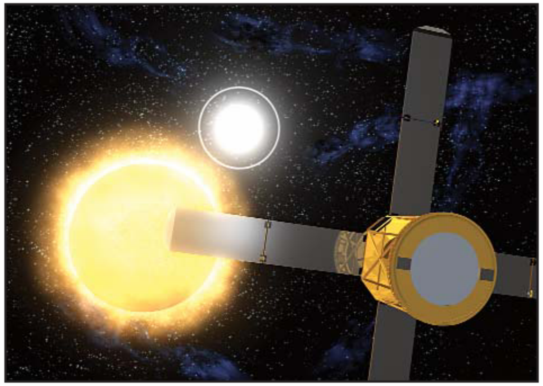
bursts occur each year, many are too distant and dim for such analysis, or they are observed well after they have faded. And a spacecraft would have to be in just the right position to catch the burst in its field of view.

A European spacecraft, launched in October, has two gamma ray instruments, and their software is being modified to make them sensitive to polarization.

The Berkeley discovery was made by the Rhessi satellite. Launched early last year, it is operated by Berkeley scientists for the National Aeronautics and Space Administration. Though primarily an X-ray observatory, the satellite is also equipped to detect gamma rays.

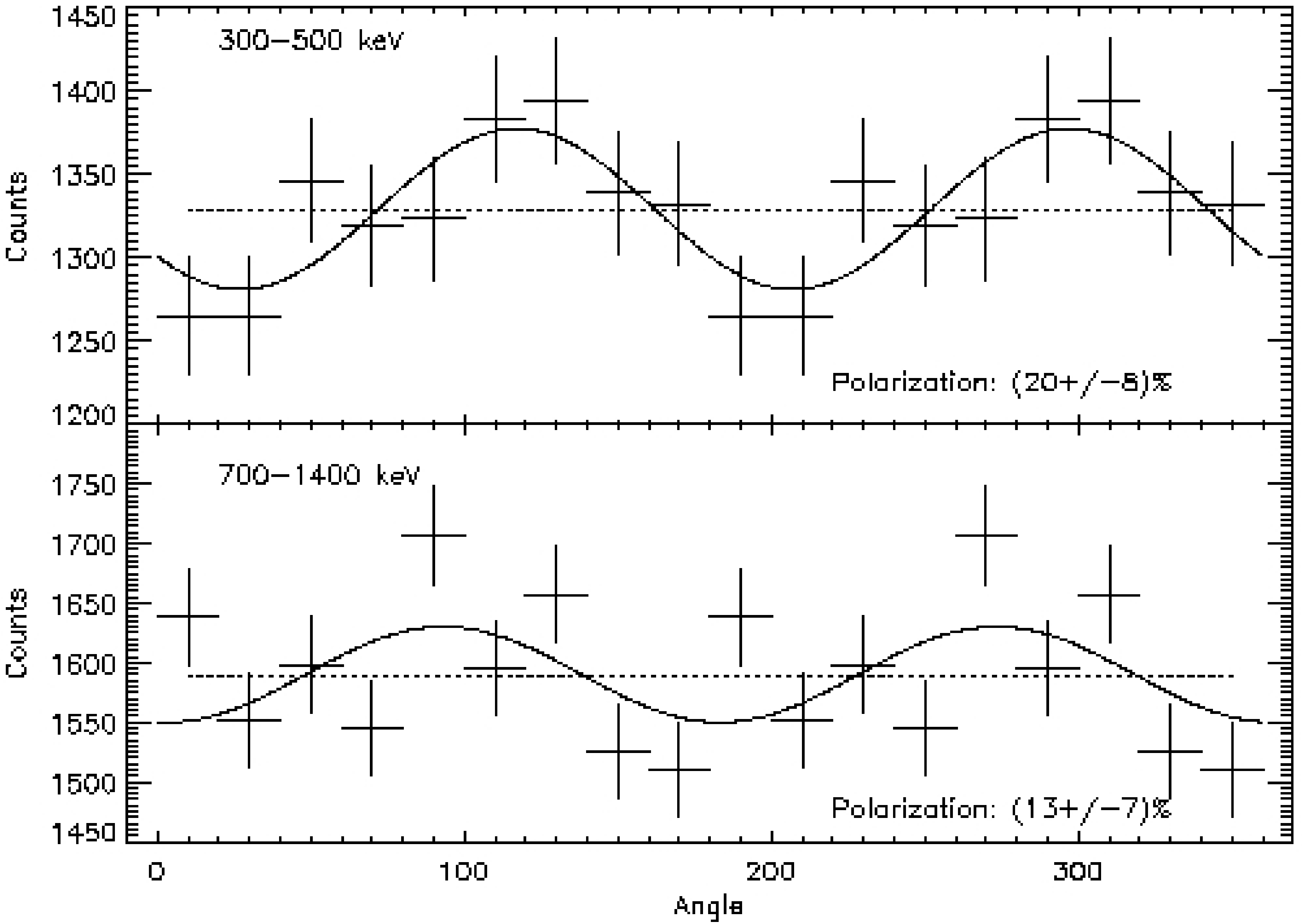
On Dec. 6, the satellite picked up a flood of gamma rays from a burst designated GRB021206. The burst peaked for about 6 seconds and then faded over 30 seconds. The measured gamma rays, the scientists reported, were 80 percent polarized, about the maximum possible polarization from electrons that spiral around magnetic fields.

"It is very surprising that this is so



Solar stare. In an artist's conception, the RHESSI satellite catches a gamma ray burst while monitoring the sun.

CREDITS: (TOP TO BOTTOM) NRAO/AUI/NSF/STScI/NASA; NASA/WALT FEIMER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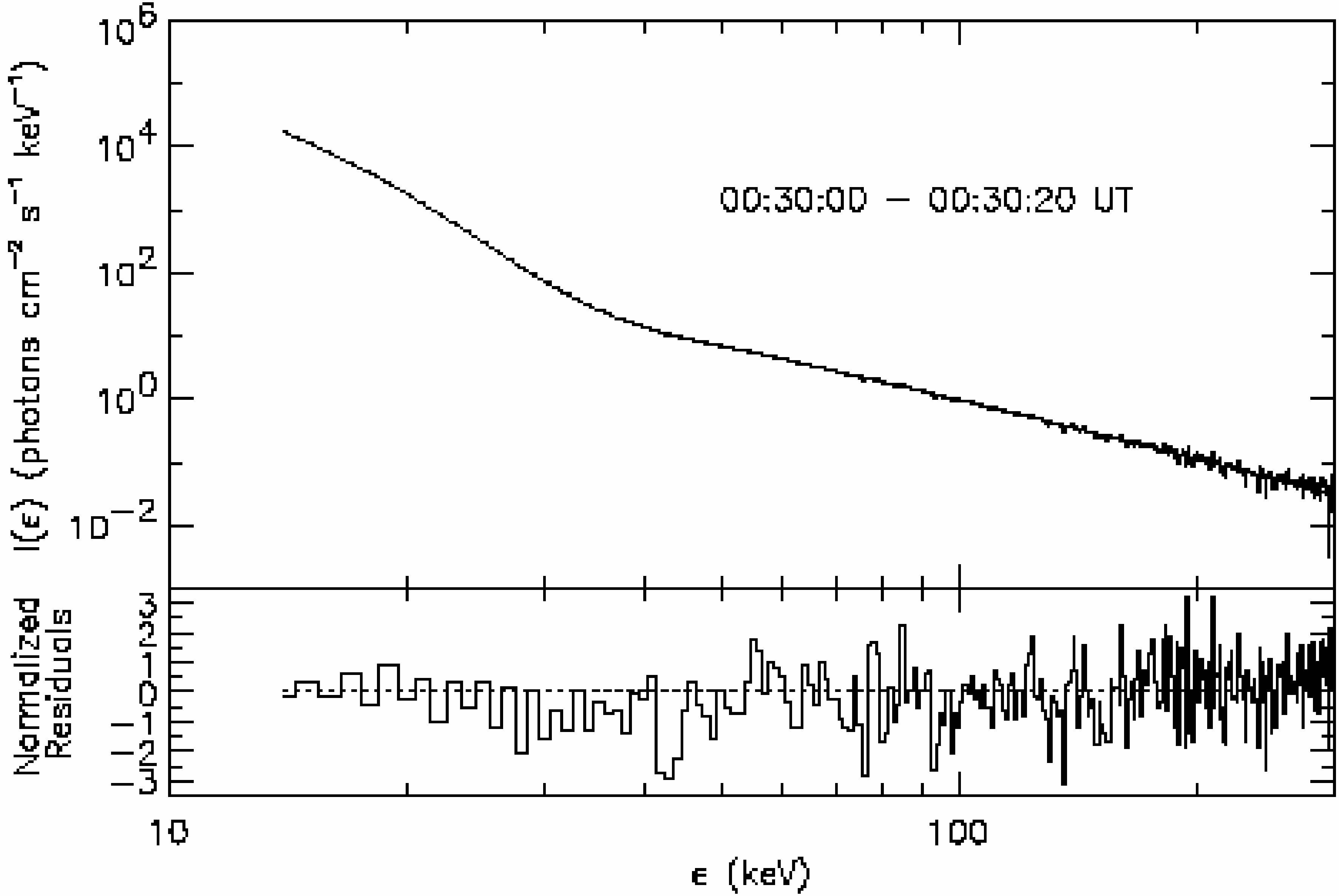

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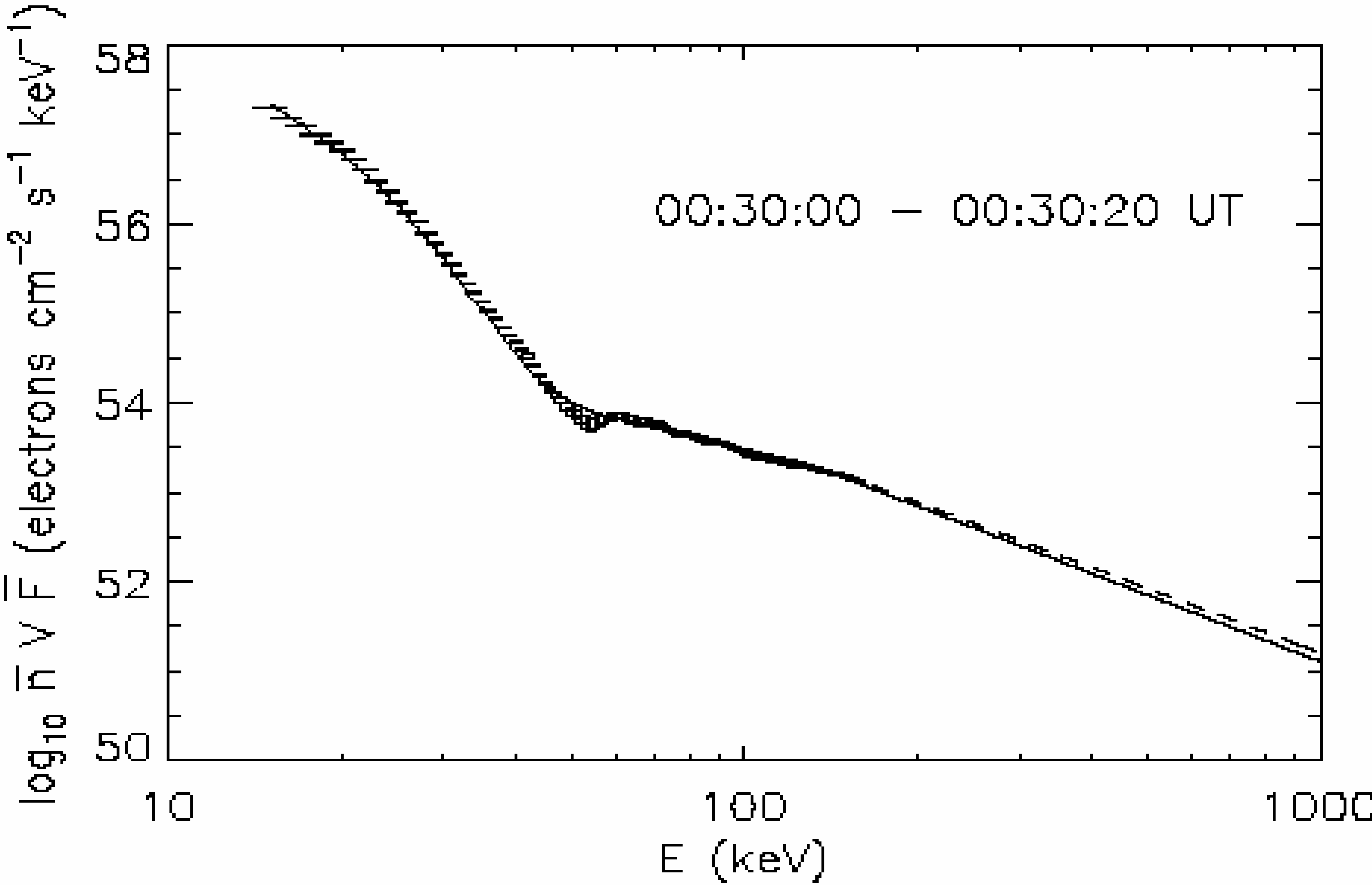

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