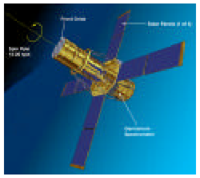
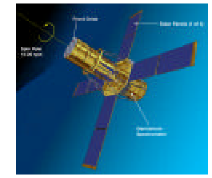


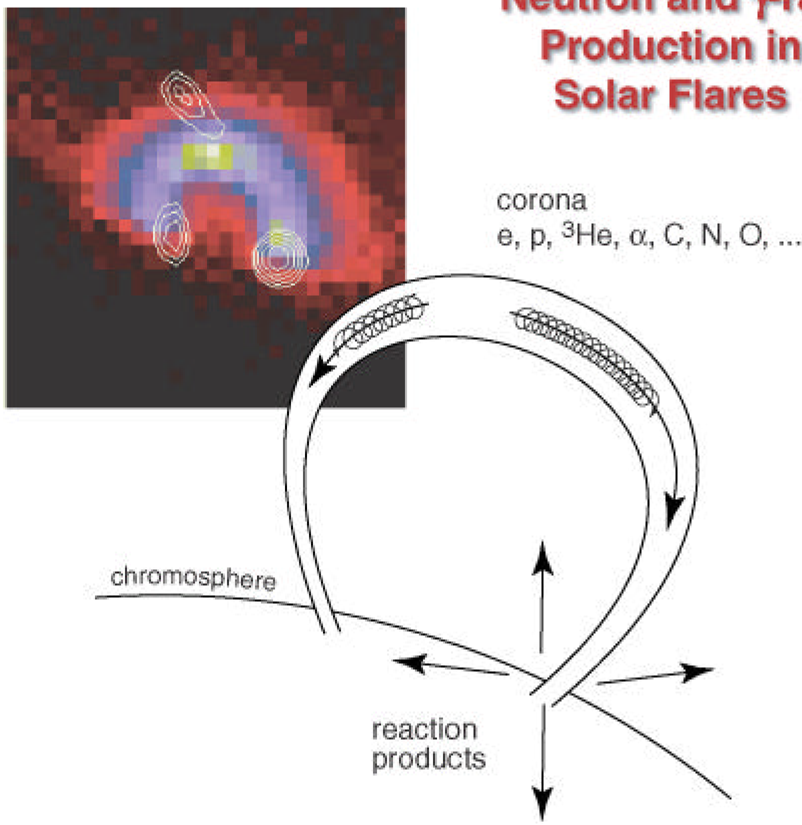
Overview

- Flare Origin of g-Rays and Neutrons
- Satellite Observations
- Spectroscopy and the Physics of Flares
- Bremsstrahlung
- Nuclear Lines (511 keV, N-capture, de-excitation)
- Ambient Abundances
- Accelerated Particle Spectra and Abundances
- Directionality of Accelerated Electrons and Ions
- Observations of Neutrons and High-Energy g-Rays from Solar Flares
- Observing the Impact of Solar Energetic Particles on the Earth
- HESSI----The Promise of Imaging/Spectroscopy

Solar γ-Ray Physics Comes of Age

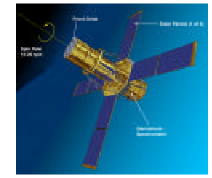


Neutron and γ-ray Production in Solar Flares



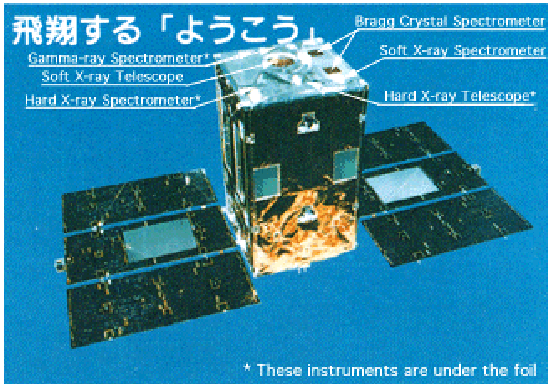
electrons:	X- and γ-ray bremsstrahlung
ions:	radioactive nuclei $\rightarrow e^{+} \rightarrow \gamma_{511}$
	$\pi \rightarrow \gamma$ (decay, $e^{\pm}$ bremsstrahlung)
	excited nuclei $\rightarrow$ γ–ray line radiation
	neutrons $\rightarrow$ { escape to space / 2.223 MeV capture line

Solar γ-Ray Physics Comes of Age

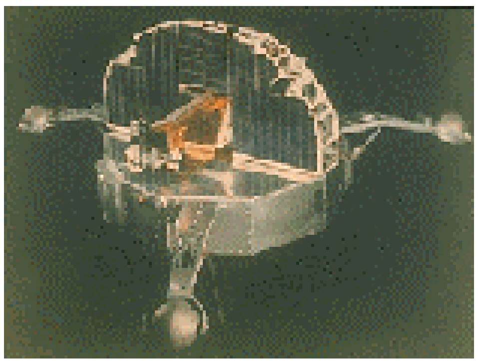


Missions Performing Solar Gamma-ray Observations

Yohkoh
(NaI / BGO)

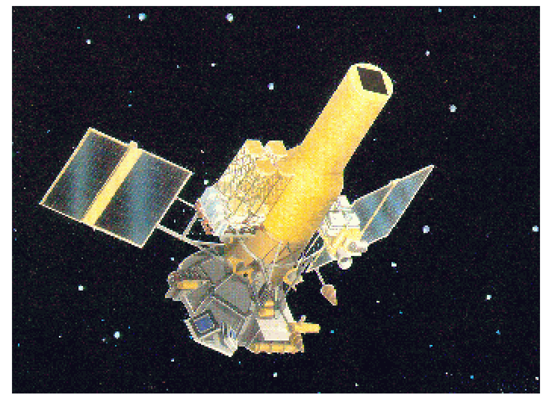


CGRO
(NaI)

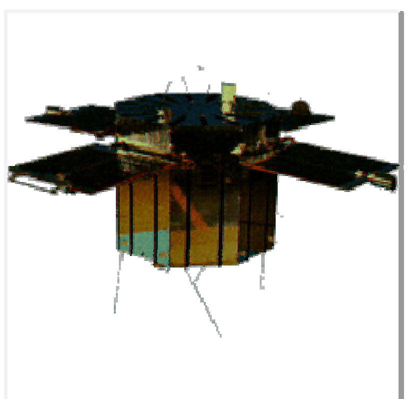


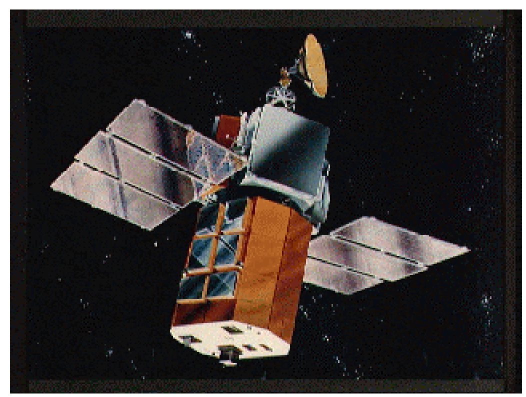
OSO-7
(NaI)

GRANAT
(BGO)

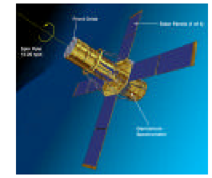


HINOTORI
(CsI)

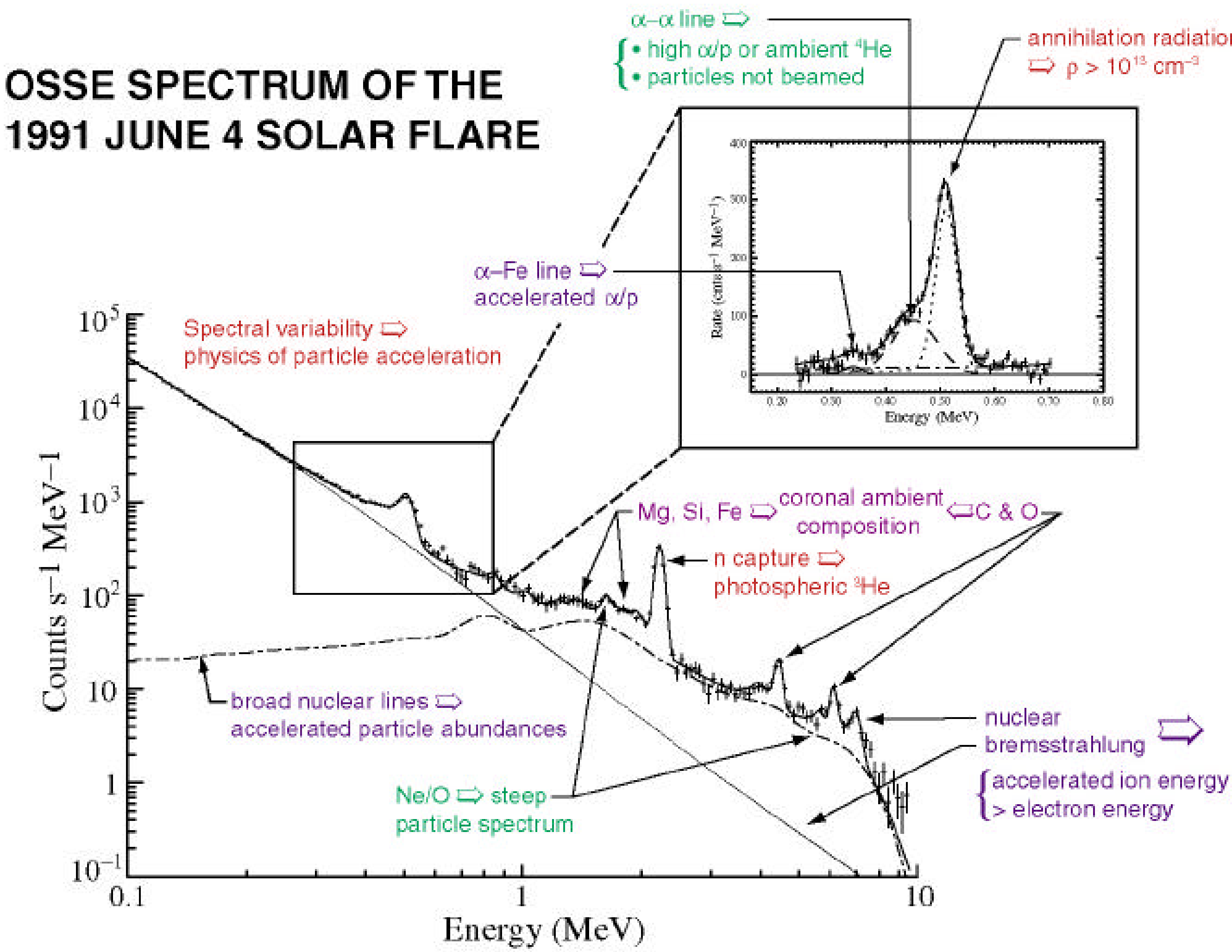


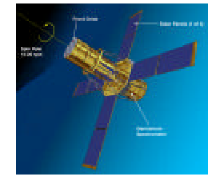


SMM
(NaI / CsI)



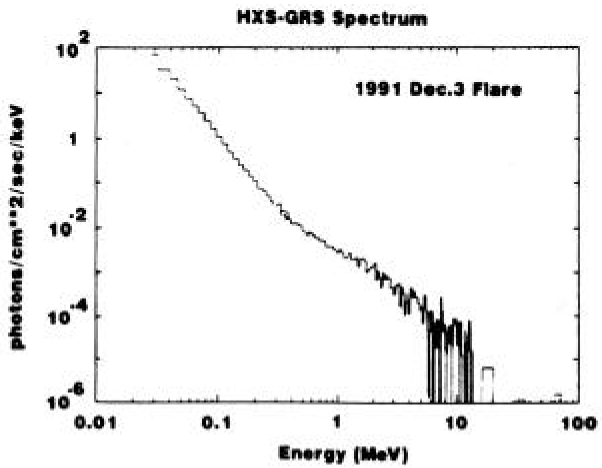
The Physics of Flares Revealed by γ-Ray Spectroscopy



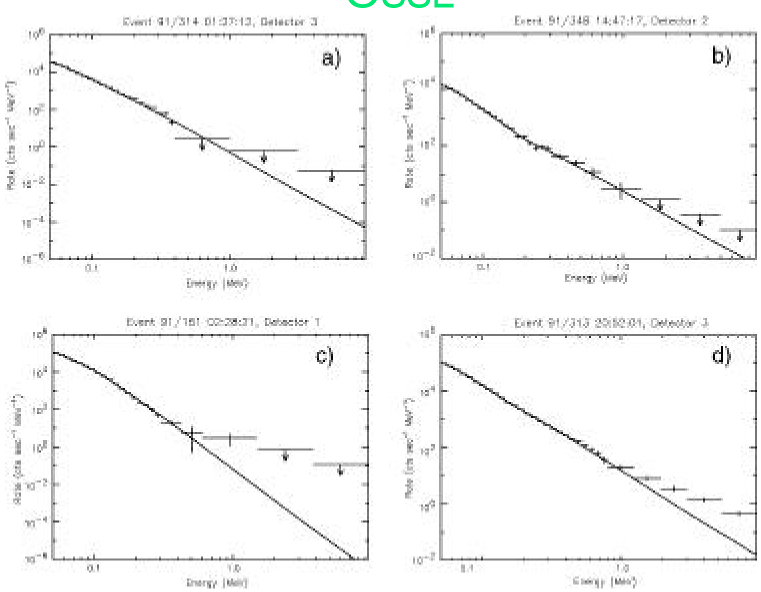


Shape of Bremsstrahlung Continuum >100 keV

Yohkoh



OSSE



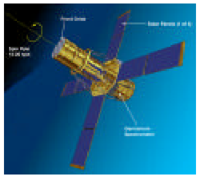
Hardening found in spectra >100 keV by combined analysis of *SMM* GRS/HXRBS spectra.

Similar hardening observed in combined spectrum from *Yohkoh* HRS/GRS.

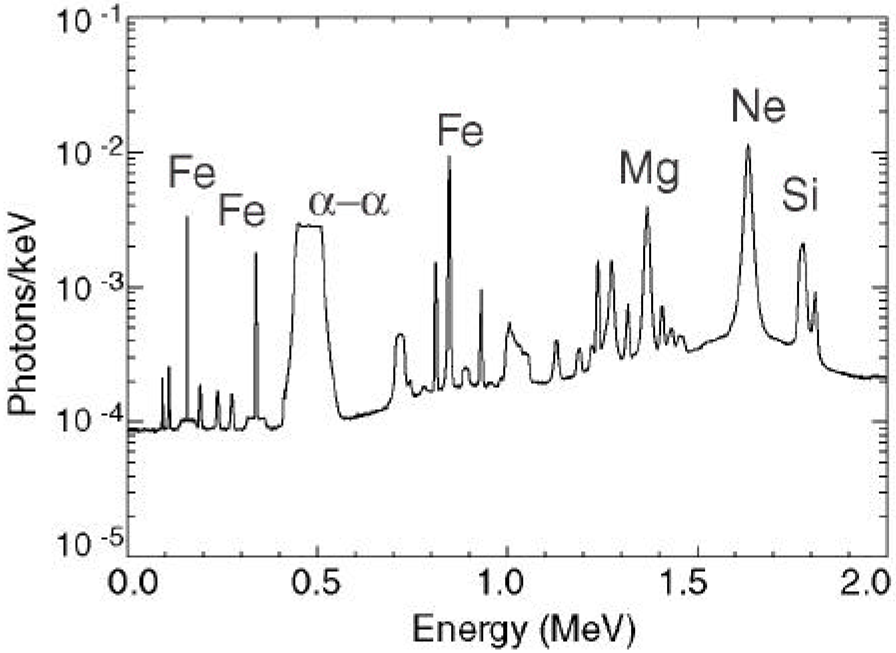
Important for measurements to be made with the same instrument.

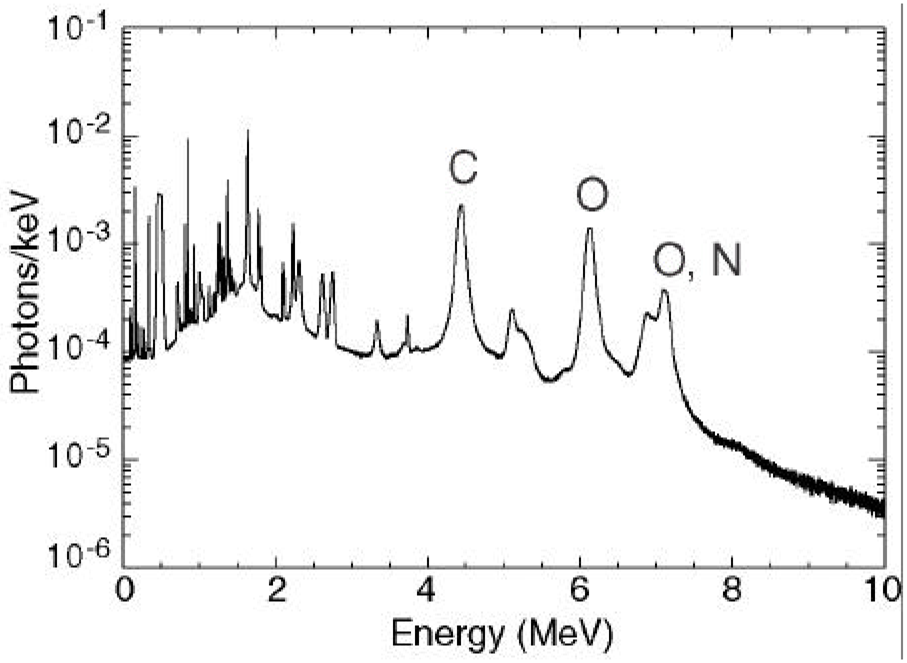
Best instruments BATSE, OSSE, and HESSI.

OSSE continuum spectra exhibit: single power laws, broken power laws with hardening and softening between ~100 and 200 keV, and additional hardening above ~1 MeV.

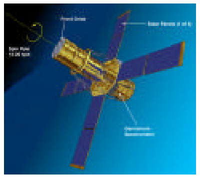


Theoretical Nuclear Line Spectrum





Ramaty, Kozlovsky, Lingenfelter, and Murphy



Narrow γ-Ray Lines Observed in Flare Spectra

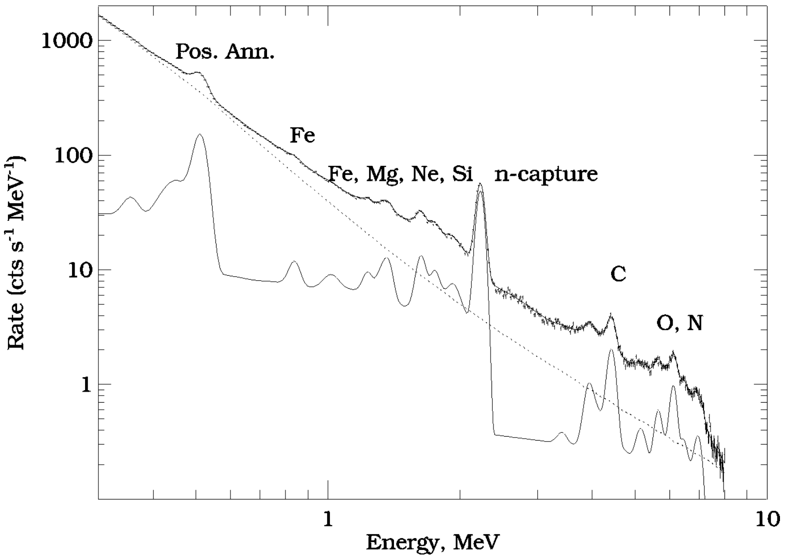
Produced by p and α interactions with ambient material.

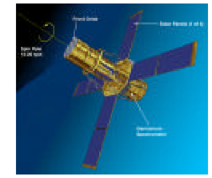
At least 30% of flares with emission >0.3 MeV exhibit γ-ray line features. *HESSI* will make more definitive measurement.

At least 19 de-excitation lines have been identified in fits to flare spectra.

Widths of de-excitation lines measured to be ~2-4% in the summed spectrum. This exceeds theory in some cases suggesting presence of blended lines (e.g. ^{14}N near ^{20}Ne) or different Doppler shifts in the flares (see later discussion).

HESSI can resolve these lines and determine intrinsic widths.

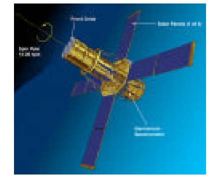




Narrow γ-Ray Lines in Solar-Flare Spectra

Sum of 19 SMM Flares

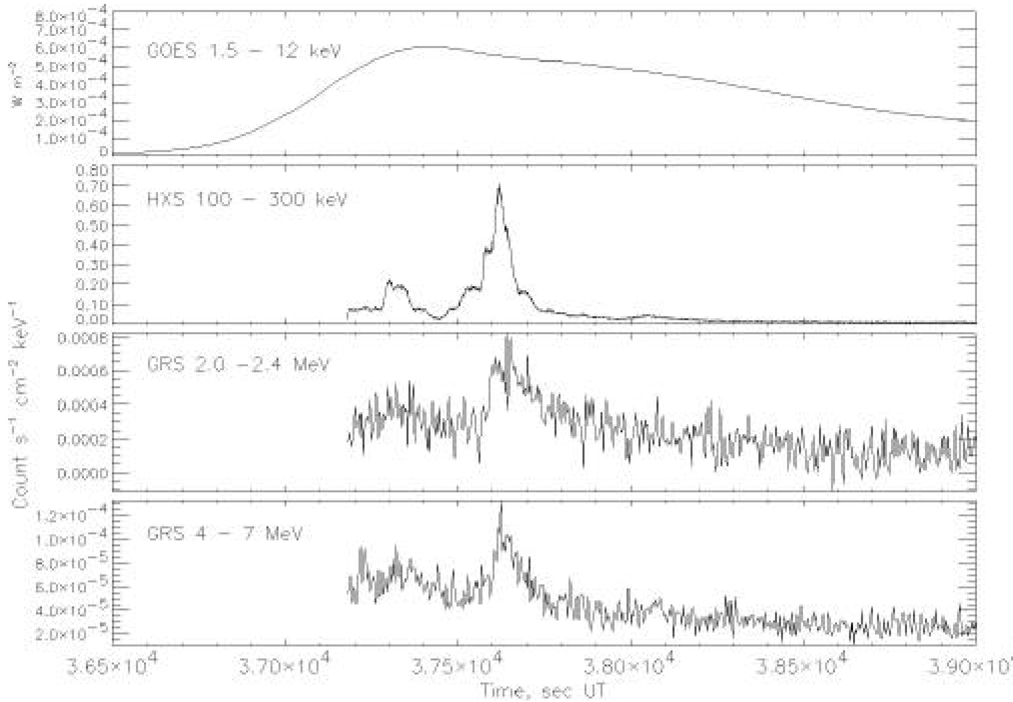
Energy, MeV	Width (% FWHM)	Identification
0.357 ± 0.002	3.7 ± 3.1	^{59}Ni (0.339 MeV)
0.454	--	^{7}Be, ^{7}Li (0.429, 0.478 MeV)
0.513 ± 0.001	< 2	e^{+}- e^{-} annihilation (0.511 MeV)
0.841 ± 0.003	--	^{56}Fe (0.847 MeV)
0.937	--	^{18}F (0.937 MeV)
~1.020	--	^{18}F, ^{58}Co, ^{58}Ni, ^{59}Ni (1.00/4/5/8)
1.234	3.3 ± 3.9	^{56}Fe (1.238 MeV)
1.317	--	^{55}Fe (1.317 MeV)
1.366 ± 0.003	3.0 ± 1.1	^{24}Mg (1.369 MeV)
1.631 ± 0.002	2.9 ± 0.6	^{20}Ne (1.633 MeV)
1.785	4.3 ± 1.5	^{28}Si (1.779 MeV)
2.226 ± 0.001	< 1.5	n-capture on H (2.223 MeV)
3.332 ± 0.030	--	^{20}Ne (3.334 MeV)
4.429 ± 0.004	3.3 ± 0.3	^{12}C (4.439 MeV)
5.200	--	^{14}N, ^{15}N, ^{15}O
6.132 ± 0.005	2.6 ± 0.3	^{16}O (6.130 MeV)
6.43	--	^{11}C (6.337, 6.476 MeV)
6.983 ± 0.015	4.0 ± 0.5	^{14}N, ^{16}O (7.028, 6919 MeV)



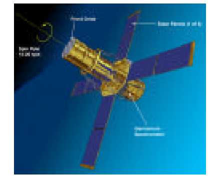
Photospheric ^{3}He/H from Neutron-Capture Line

- **Photospheric ^{3}He/H ratio provides information primordial ratio.**
- **^{3}He captures neutrons and competes with capture on H and neutron escape.**
- **2.223 MeV capture line decay can be measured. Exponential decay times of ~ 100 sec.**
- **Based on some assumptions this yields upper limits on the ^{3}He/H ratio of ~1--3 x 10^{-5}. Consistent with other estimates and nucleosynthesis.**
- **Improvements needed in measurements and modeling.**

BASTILLE DAY FLARE, 2000 JULY 14



Yohkoh Observation

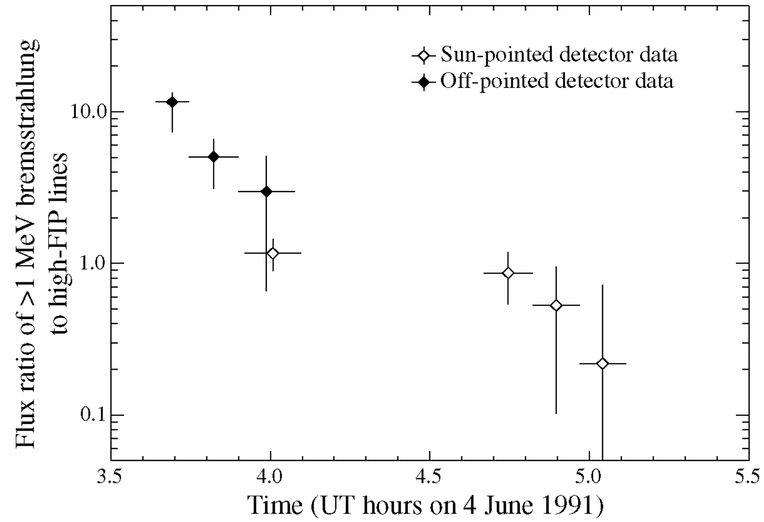


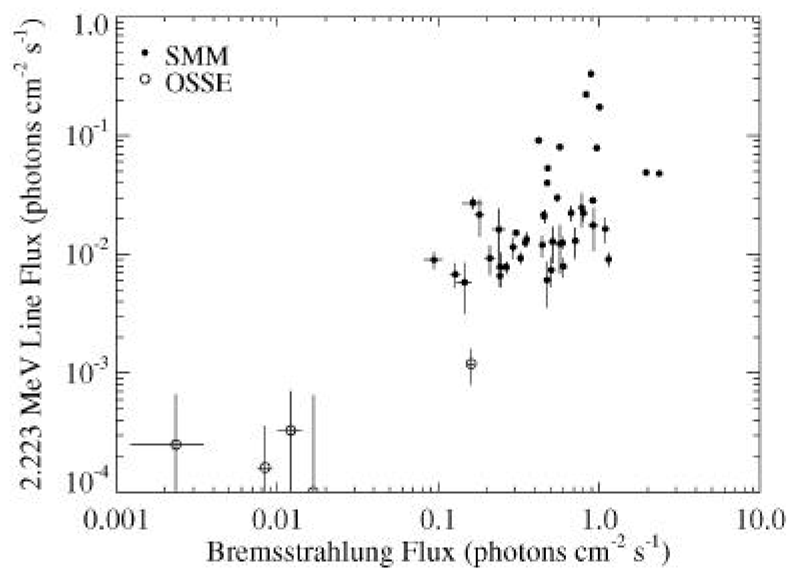
Threshold for Ion Acceleration in Flares

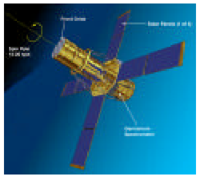
Best signature for ion acceleration is n-capture line at 2.223 MeV (away from limb). Confirmation using de-excitation lines and annihilation line important.

Line to bremsstrahlung continuum ratio is highly variable within flares and from flare-to-flare (e.g. ‘electron dominated events’). Upper panel shows variation of bremsstrahlung to nuclear line ratio for the 1991 June 4 flare observed by OSSE.

No evidence to date for a ‘threshold’ for ion acceleration as seen by comparison of 2.223 MeV line observed by OSSE and SMM Requires clear identification of narrow line-- *HESSI*.





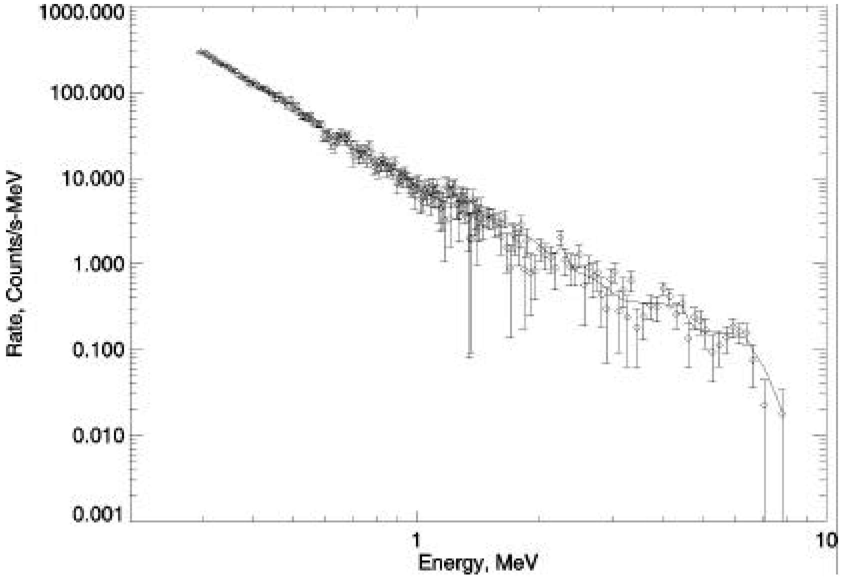


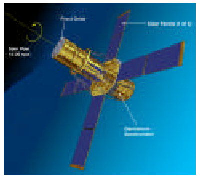
EVIDENCE FOR GAMMA-RAY EMISSION IN HARD X-RAY FLARES

Summation of spectra from 40 flares that individually did not extend above 1 MeV.

Emission in summed spectrum clearly extends up to about 8 MeV.

Is it nuclear?





Spectroscopy of e^+-e^- Annihilation

Positrons can annihilate in flight and after formation of positronium.

Positronium breaks down at high temperature.

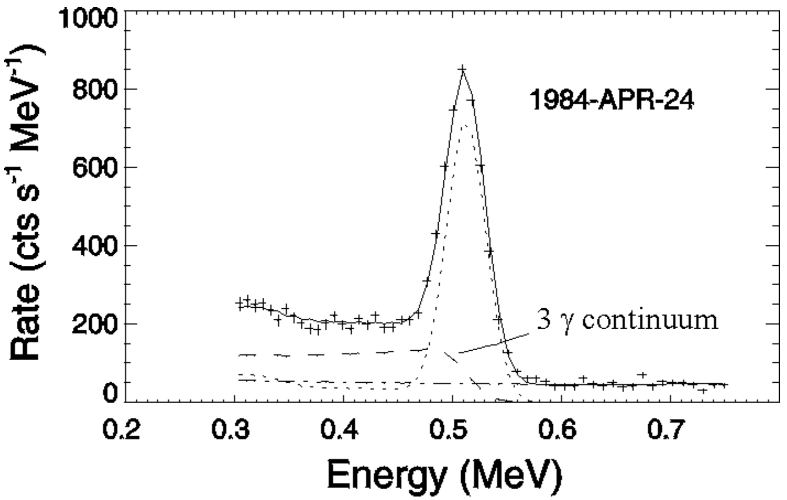
Positronium annihilation results in 2 or 3 γ's depending on ambient density.

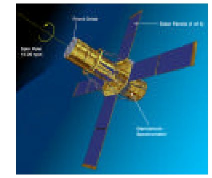
Line width yields information on temperature and density.

Good spectral resolution needed to separate line, continuum, and α-α fusion lines.

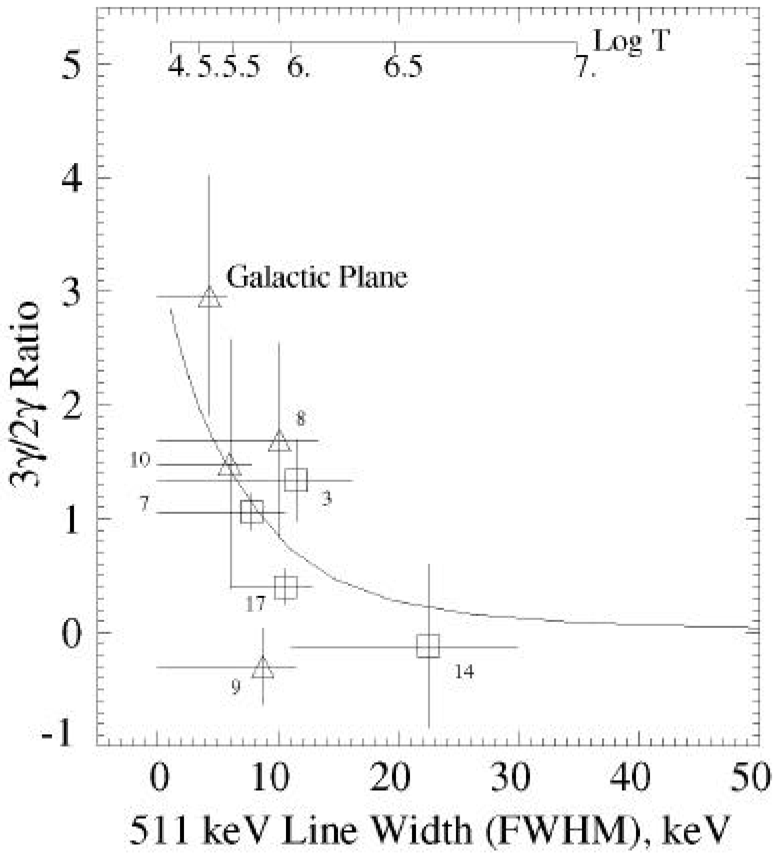
Measurements of some *SMM* flares have been performed.

HESSI measurements are required.





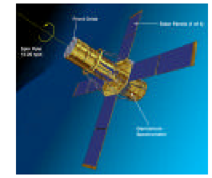
Annihilation Line Width and Continuum Studies



The positronium continuum is suppressed in flares compared with the Galactic Center.

Intrinsic line width has been measured in at least one flare (14). Continuum is suppressed by high T.

Continuum strongly suppressed in at least one other flare (9). Could it be due to high density ($>10^{14}$ cm^{-3})?



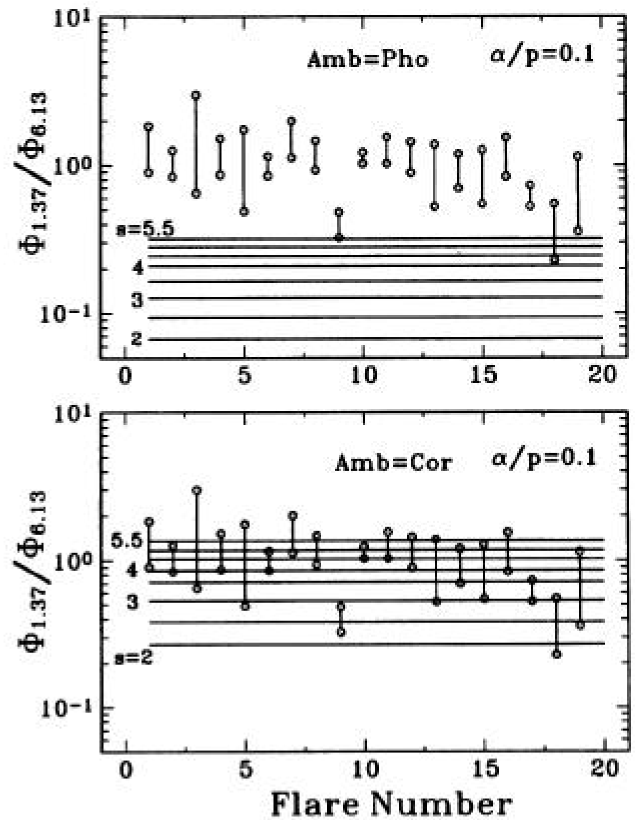
Composition of Ambient Medium from γ-Ray Lines

Low FIP (first ionization potential) elements enhanced in the corona.

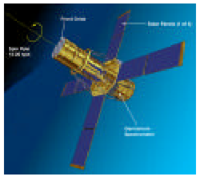
Comparison of lines from low and high FIP elements in flare spectra suggests coronal composition for average ambient flare plasma.

Evidence for flare-to-flare variability in low FIP/high FIP ratio.

Is there a correlation between ambient composition and density? Flare #9 had the weakest annihilation continuum and lowest FIP ratio.



Ramaty, Kozlovsky, Mandzhavidze, and Murphy



Temporal Change in Ambient Composition?

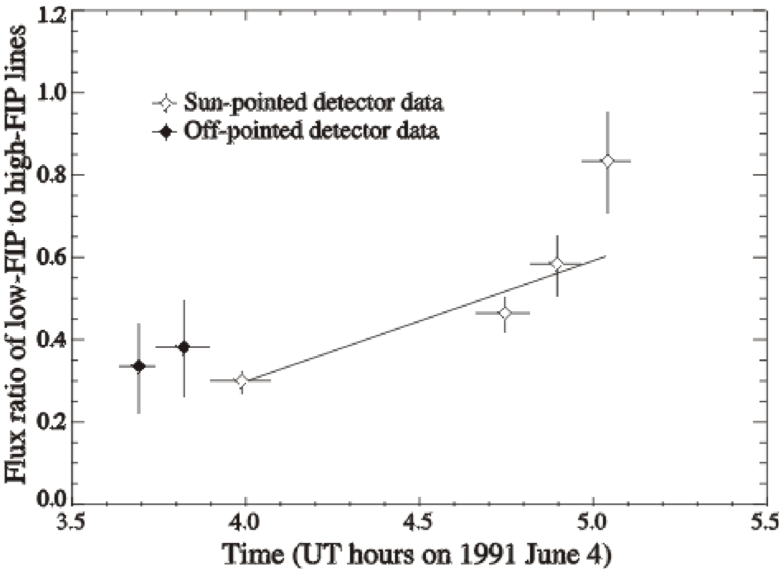
CGRO/OSSE has observed increases in the low-FIP/high-FIP line ratio during the decay phase of flares.

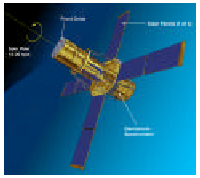
This suggests that the ambient composition changes during the flare.

This could arise due to introduction of coronal material or by increase in altitude where interactions take place.

Does the 3γ /2γ annihilation ratio show a similar increase in time? Is there a change in the annihilation line width?

Important objective for *HESSI*.





Spectral Variability in a Long Duration Flare

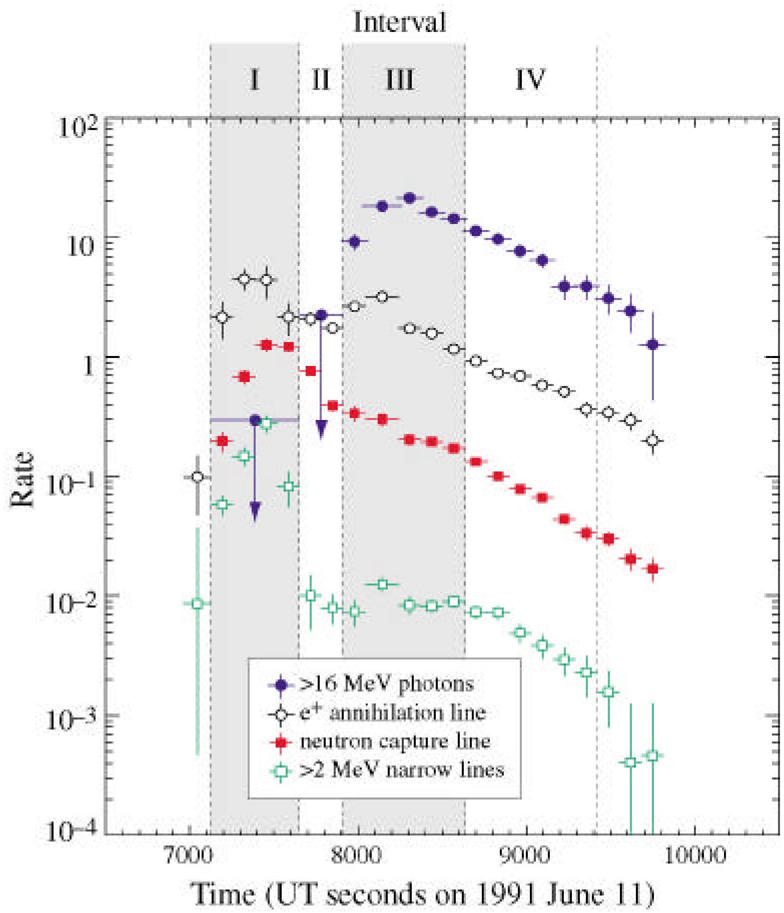
CGRO/EGRET observed high energy γ-rays several hours after the impulsive phase of the 1991 June 11 flare.

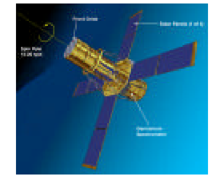
This same flare was well observed by *CGRO* during the impulsive phase. Four intervals identified by Dunphy et al.

>16 MeV γ-rays were detected during the 3rd interval. This broad peak was not detected in the de-excitation and 2.223 MeV lines, but appears to have been observed in the annihilation line.

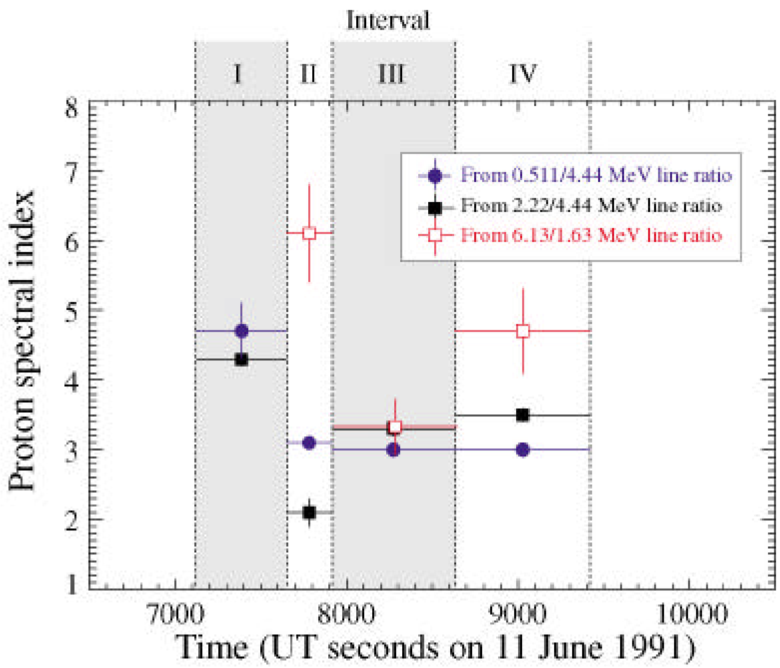
Suggests that the peak is due to pion production.

HESSI obtain arc sec images of the annihilation line and therefore will image the pion-production region.6





Measuring Particle Spectra Using γ-Ray Lines



Line ratios provide estimates of the spectral indices of flare accelerated particles in different energy ranges.

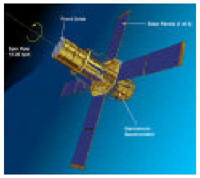
6.13/1.63 MeV ~2 - 20 MeV/nucleon

2.22/4.44 MeV ~10 - 100 MeV/nucl.

0.51/4.44 MeV ~10 - 500 MeV/nucl.

Ratios suggest: a single power law for accelerated particles from 2 to several 100 MeV during interval III; a spectrum that hardens with energy in the decay phase of the flare.

These measurements yield estimates of the energy contained in accelerated ions.



Ion/Electron Energetics from γ-Ray Spectroscopy

Using the spectral indices determined from the line ratios and the flux in the strong carbon line we can estimate the energy in accelerated ions.

Ramaty and Mandzhavidze (1999) have calculated energies contained in electrons (>20 keV) and ions (> 1 MeV/nucleon) in 19 flares based on *SMM*/HXRBS and GRS data.

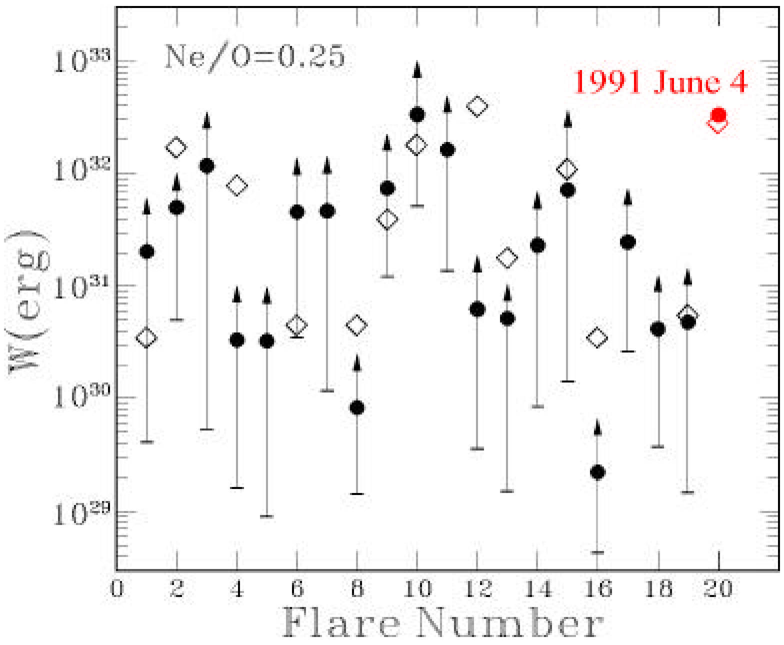
Diamonds --- electrons

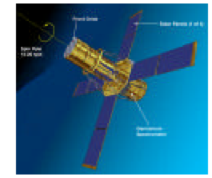
Filled circles --- ions

Energy in accelerated particles appears to be equi-partitioned between electrons and ions.

***CGRO*/OSSE measurement of 1991 June 4 flare is consistent with conclusion.**

Important to extend measurements to energies <1 MeV using weak proton radiative capture lines.



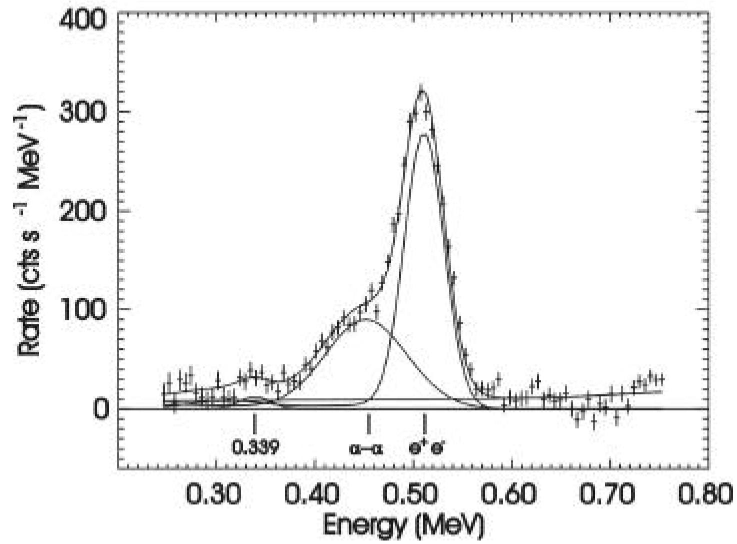


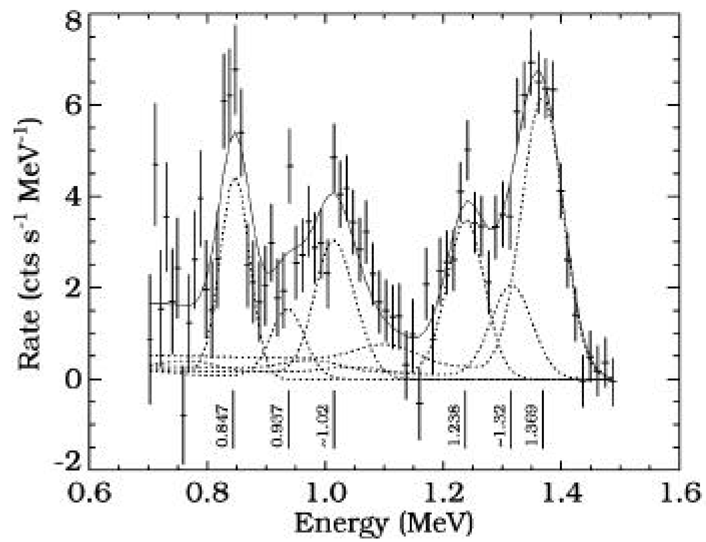
Helium Abundance from γ-Ray Line Spectra

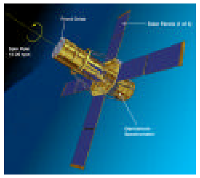
Relative intensity of the α-α line feature suggests either enhanced accelerated α/p ratio or enhanced ambient He/H ratio at the flare site.

Intensities of lines at 0.339 and ~1.03 MeV from α-^{56}Fe can discriminate between the two. There are other lines near 1.03 from p and ^{3}He interactions on C & O that complicate the situation. A line near 0.937 MeV is also expected from the ^{3}He interaction.

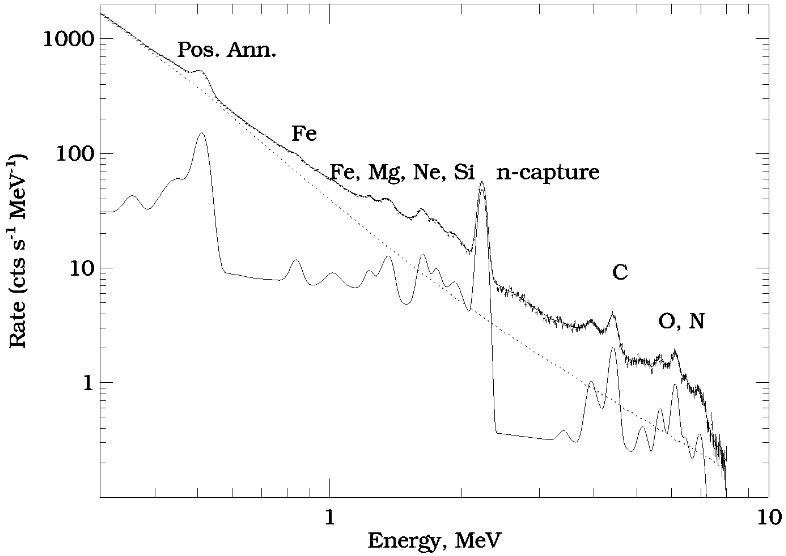
Study of 19-flare average suggests enhanced α/p and evidence for ^{3}He/^{4}He at levels near 0.1 (Share & Murphy (1998). Study of individual flares suggest that ambient He/H can also be enhanced and that ^{3}He/^{4}He can be as high as ~1 (Mandzhavidze et al. 1999) . *HESSI* observations are key!







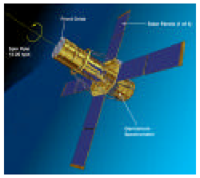
Revealing the Spectrum from Accelerated Heavy Ions



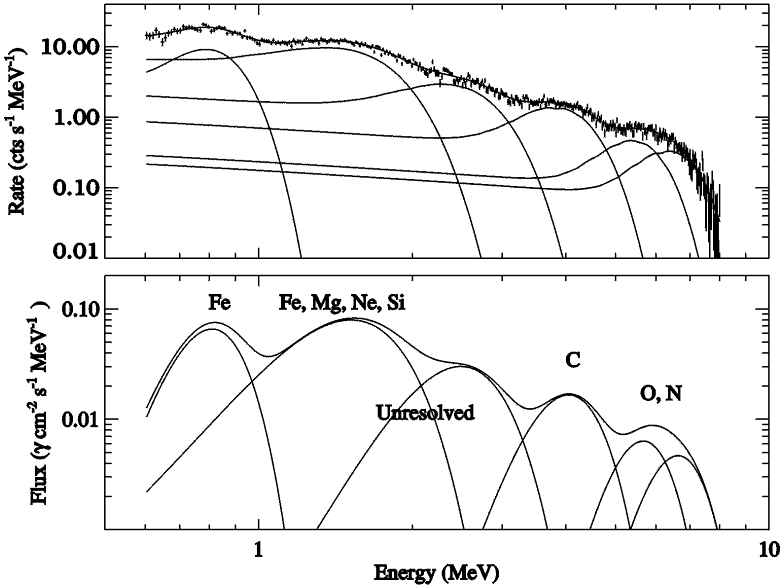
Accelerated heavy ions are excited by interaction with ambient H.

De-excitation lines from these ions are expected to be Doppler broadened by ~25%.

Broad line spectrum is revealed by subtracting best fitting narrow-line and bremsstrahlung components shown for sum of 19 flares observed by the *SMM*/GRS.



Gamma-Ray Spectrum from Accelerated Heavy Ions

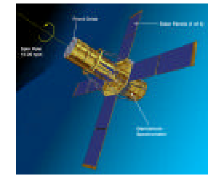


Residual spectrum after subtracting contributions from bremsstrahlung and narrow lines reveals broadened lines from accelerated ions.

Best fit to spectrum contains six Gaussian features that can be identified with different ions.

Fe and C are resolved. The Fe, Mg, Ne, and Si lines between 1 - 2 MeV cannot be resolved.

Major uncertainty is the shape of the 'unresolved line' component that is expected to peak in the 1 - 3 MeV region.



Broadened Lines Identified in γ-Ray Spectra

Energy, MeV	Width, MeV	Identification	Enhancement	
			γ-Rays	SEP's
0.81 ± 0.01	0.25 ± 0.02	^{56}Fe	7.8 ± 1.9	6.7 ± 0.8
1.52 ± 0.02	0.78 ± 0.05	Unresolved, ^{56}Fe, ^{24}Mg, ^{20}Ne, ^{28}Si	2.4 ± 0.4	
		^{24}Mg, ^{20}Ne, ^{28}Si		~2.7
2.49 ± 0.07	1.05 ± 0.17	Unresolved lines		
4.04 ± 0.05	1.26 ± 0.15	^{12}C	1	1
5.67 ± 0.19	1.5	^{16}O	0.9 ±0.2	1.1 ±0.1
6.63 ± 0.16	1.7	^{14}N, ^{16}O	1.3 ± 0.4	

Lines appear to be red-shifted by ~5 - 9 %.

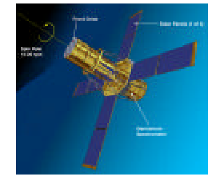
Lines are broadened by ~30%.

Some shift and broadening may be due to summing of 19 spectra.

Enhancement (γ-ray) = $(Fe_{brd}/Fe_{nar})/(C_{brd}/C_{nar}) * Z^2/A$.

O and Fe enhancements in good agreement with SEPs.

Mg, Si, Ne enhancement is upper limit due to unknown contribution from unresolved lines. This suggests higher temperatures than inferred from SEP's.



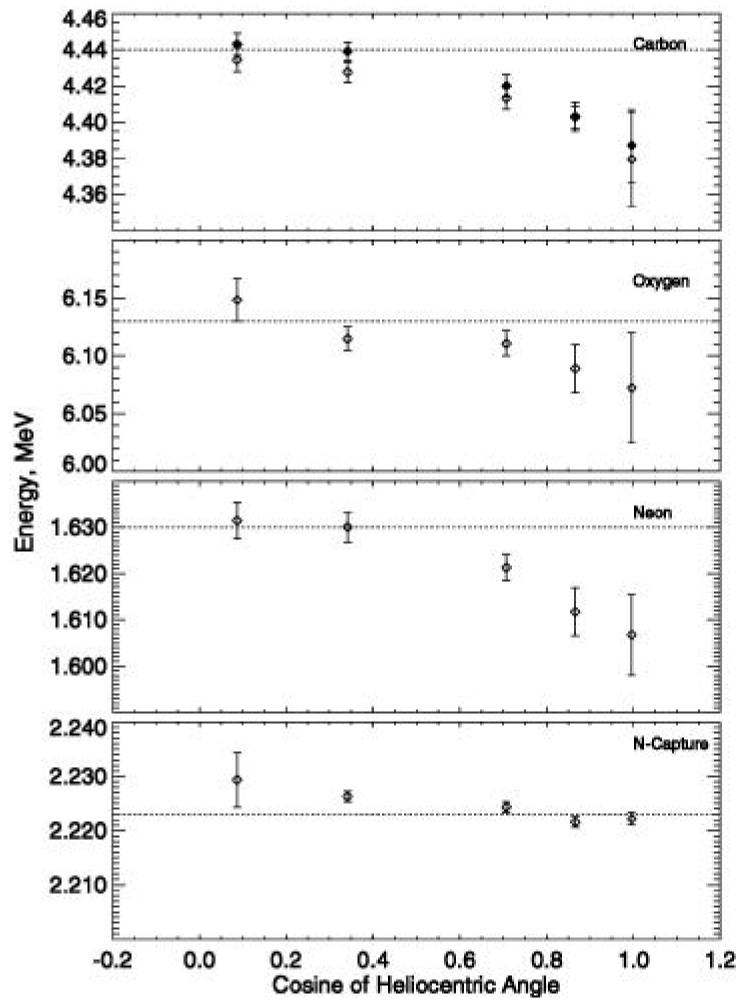
Directionality of Accelerated Ions Inferred from Narrow Lines

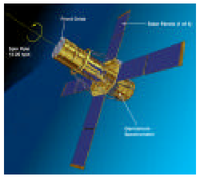
Energies and widths of g-ray lines from ambient nuclei excited by flare-accelerated p's and a's provide information on their directionality.

Figure shows fitted energies of 4 lines from flares observed at 5 heliocentric angles.

C, O, and Ne lines red-shifted by as much as ~1% (no significant shift in n-capture line). Yohkoh/GRS observation of the Bastille day flare confirms shift in carbon.

Suggests downward distribution of accelerated particles or an isotropic distribution in a medium that has a significant density gradient





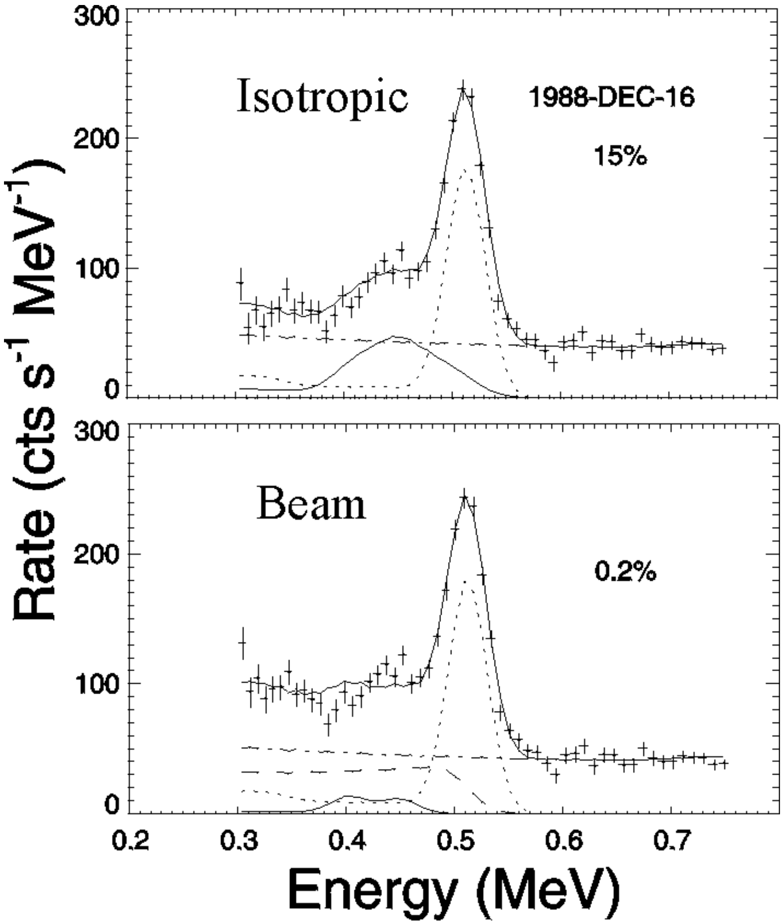
Directionality of Alpha Particles

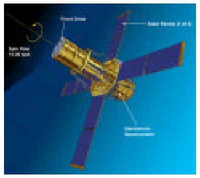
Line shape of α-α fusion lines in two flares is inconsistent with a downward beam and is consistent with isotropic or fan-beam distributions.

Width may be narrower and shifted in energy relative to isotropic model. Comparison with improved models important.

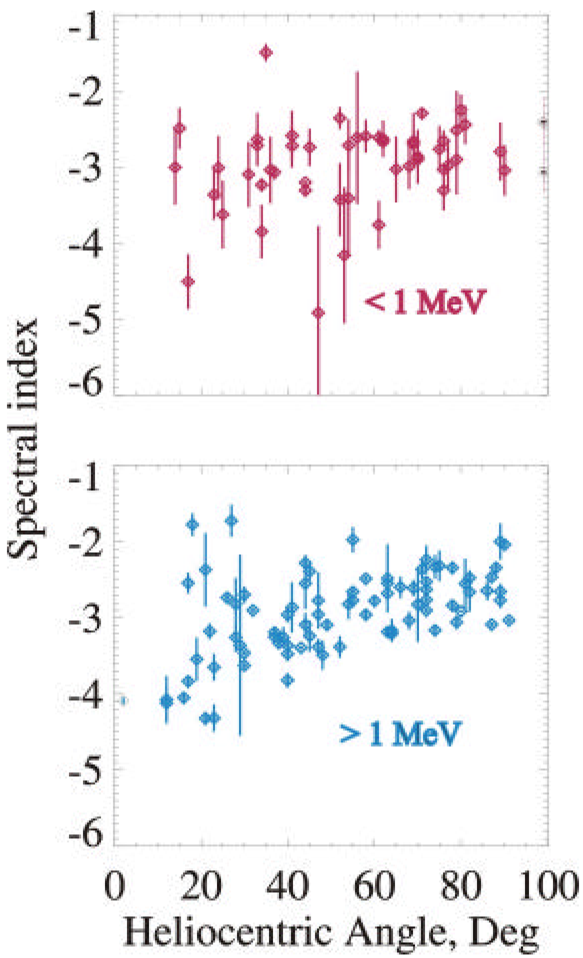
A downward isotropic distribution is marginally consistent with the data.

HESSI measurements will clarify the directionality of accelerated α-particles.





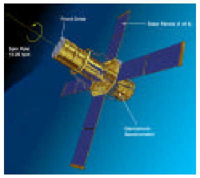
Directionality of Accelerated Electrons



Stereoscopic measurements at ~100 keV suggested an isotropic distribution of accelerated electrons.

Hardening of average bremsstrahlung spectrum with heliocentric angle suggests that accelerated electron distribution is not isotropic. A fan beam distribution can explain this behavior.

Panel to left may explain this difference. Low energy emission may be isotropic and higher energy emission exhibits the directionality.



Annihilation Line as Monitor for Pions

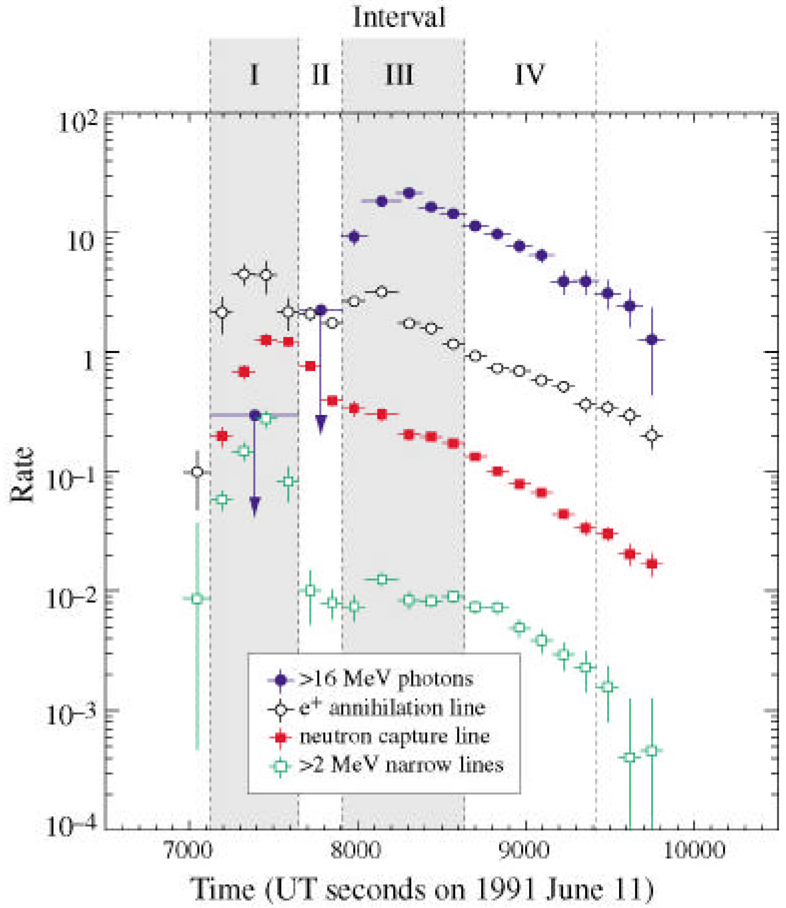
CGRO/EGRET observed high energy γ-rays several hours after the impulsive phase of the 1991 June 11 flare.

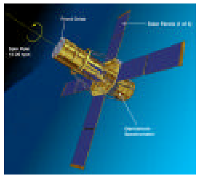
This same flare was well observed by *CGRO* during the impulsive phase. Four intervals identified by Dunphy et al.

>16 MeV γ-rays were detected during the 3rd interval. This broad peak was not detected in the de-excitation and 2.223 MeV lines, but appears to have been observed in the annihilation line.

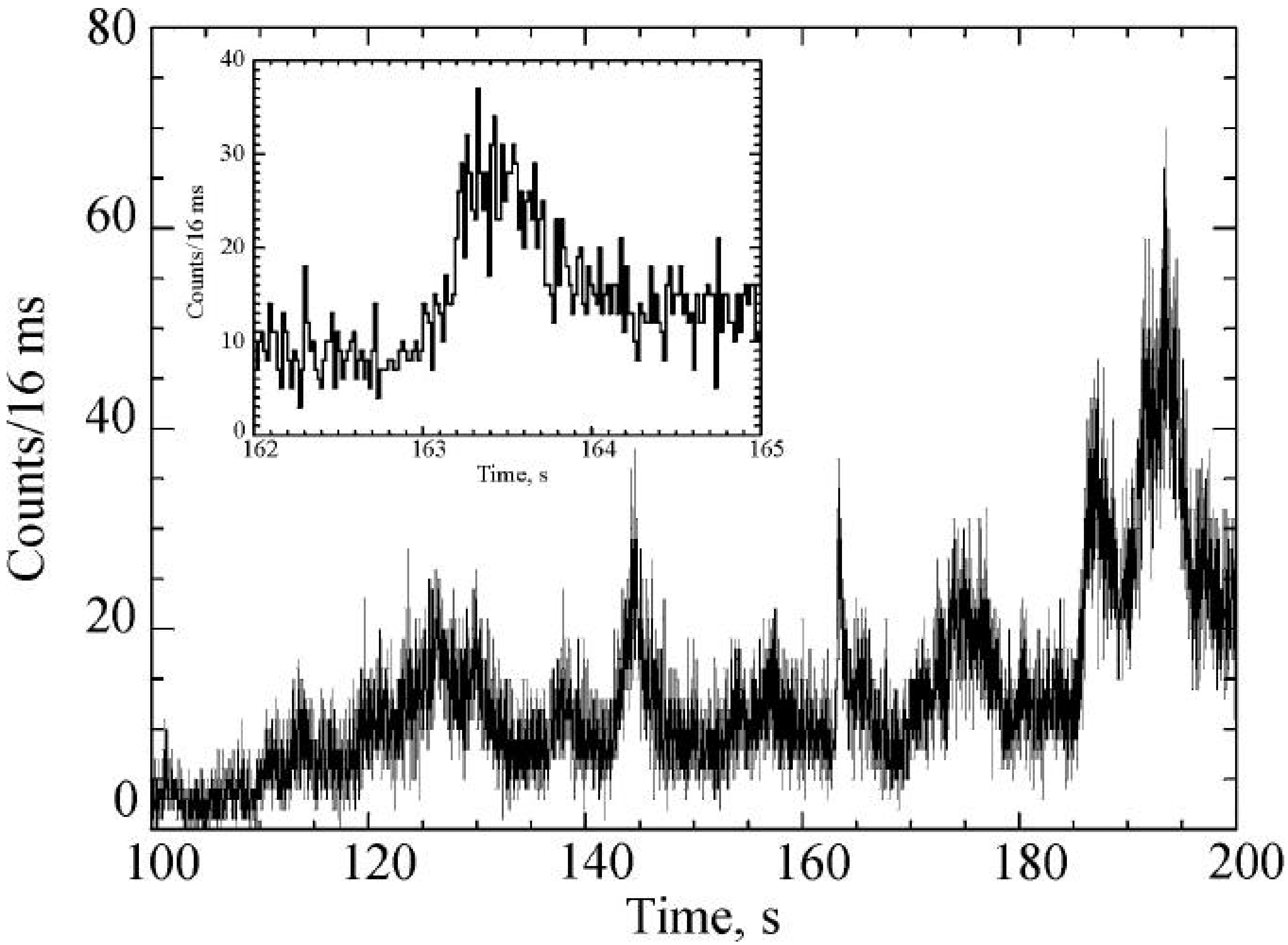
Suggests that the peak is due to pion production.

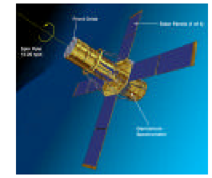
HESSI obtain arc sec images of the annihilation line and therefore will image the pion-production region.6



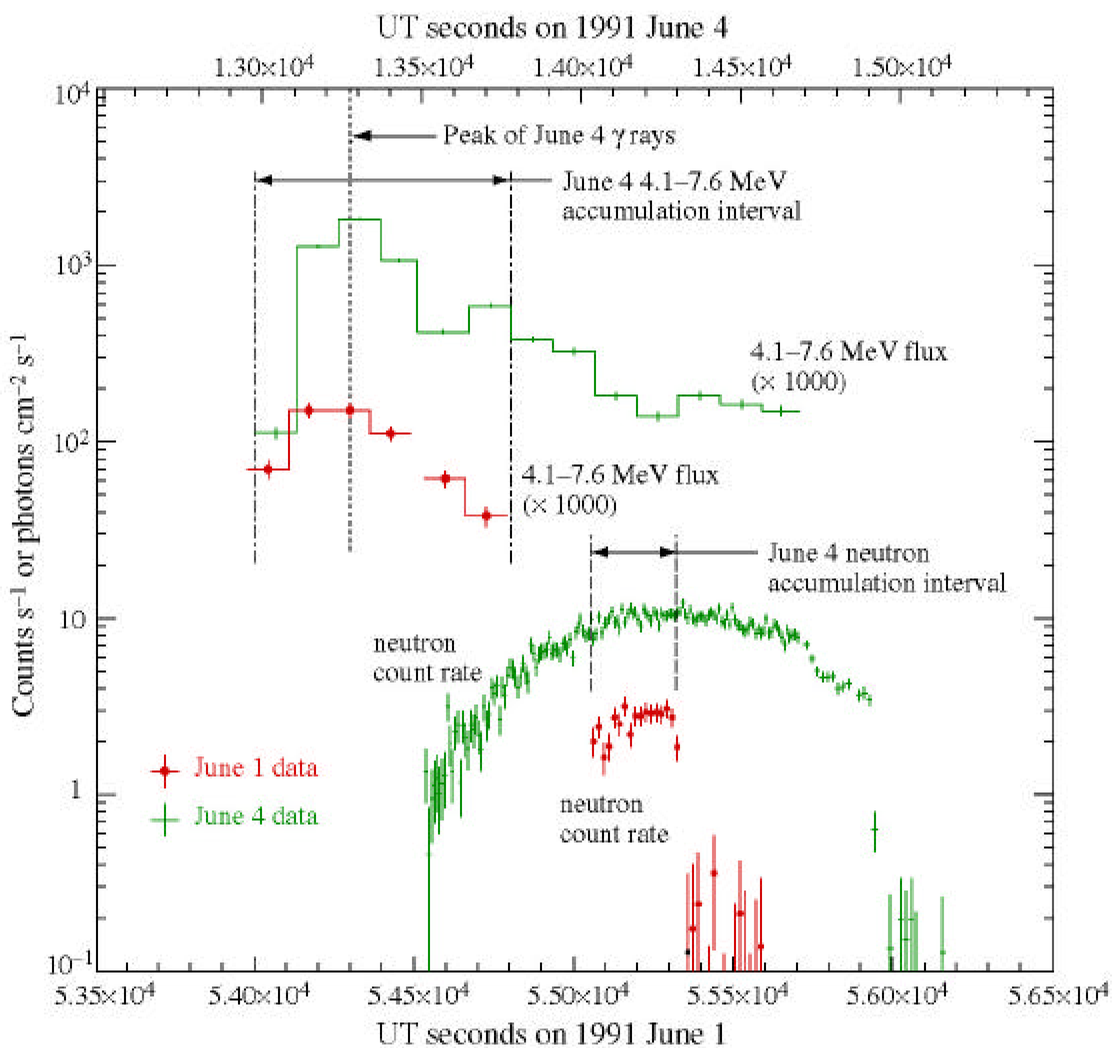


100 MS TIME STRUCTURE IN FLARES OBSERVED >15 MEV

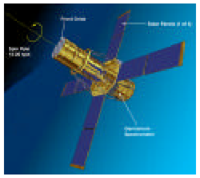




γ Rays and Neutrons Observed from the 1 & 4 June 1991 Flares



OSSE and GRANAT



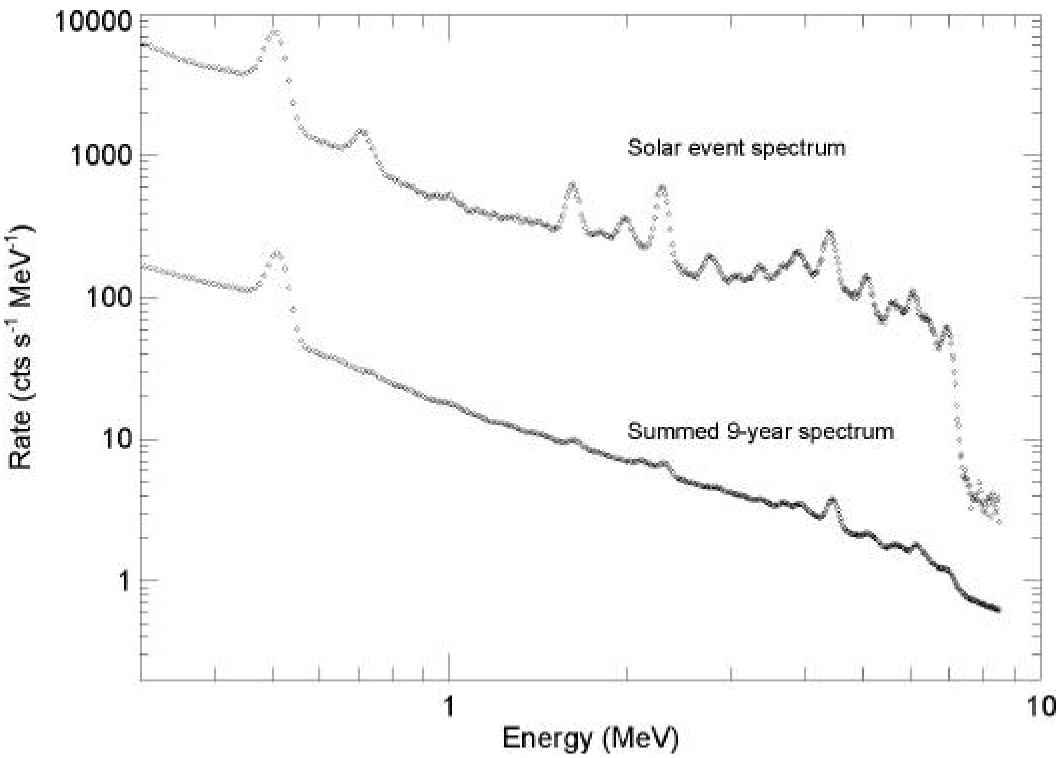
Earth's Atmosphere Glows in γ-Rays

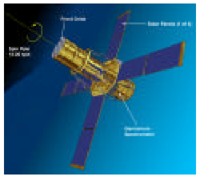
Atmospheric g rays are produced by cosmic-interactions in the Earth's atmosphere. This quiescent spectrum is shown on the lower plot.

Protons from the 1989 October 20 solar energetic particle event produced the upper spectrum.

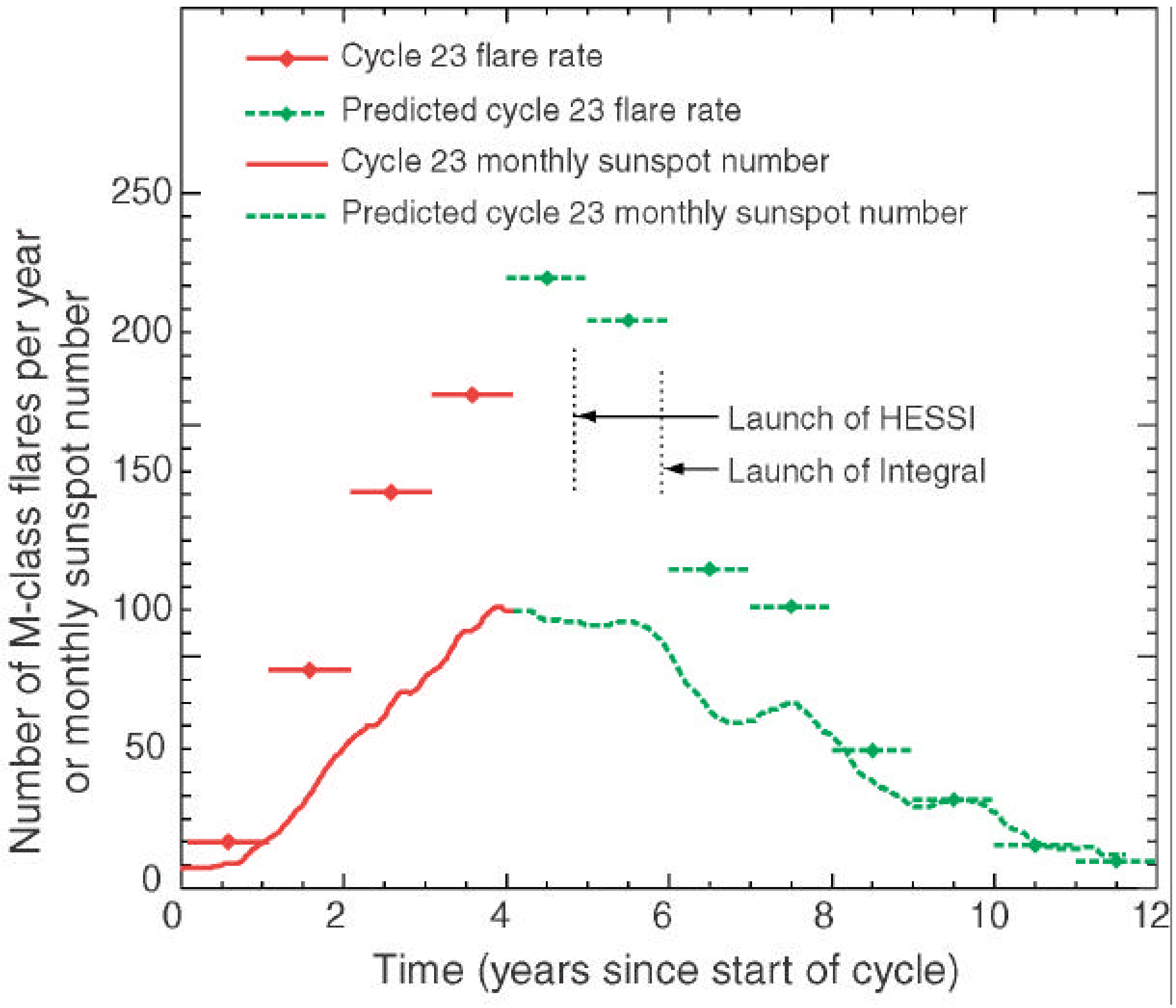
The Yohkoh GRS observed a similar spectrum from the 2000 July 15 SEP event.

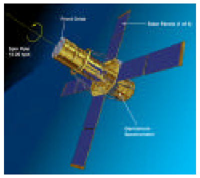
These atmospheric observations showed that the 2000 July proton spectrum was much softer, consistent with observations made in space.



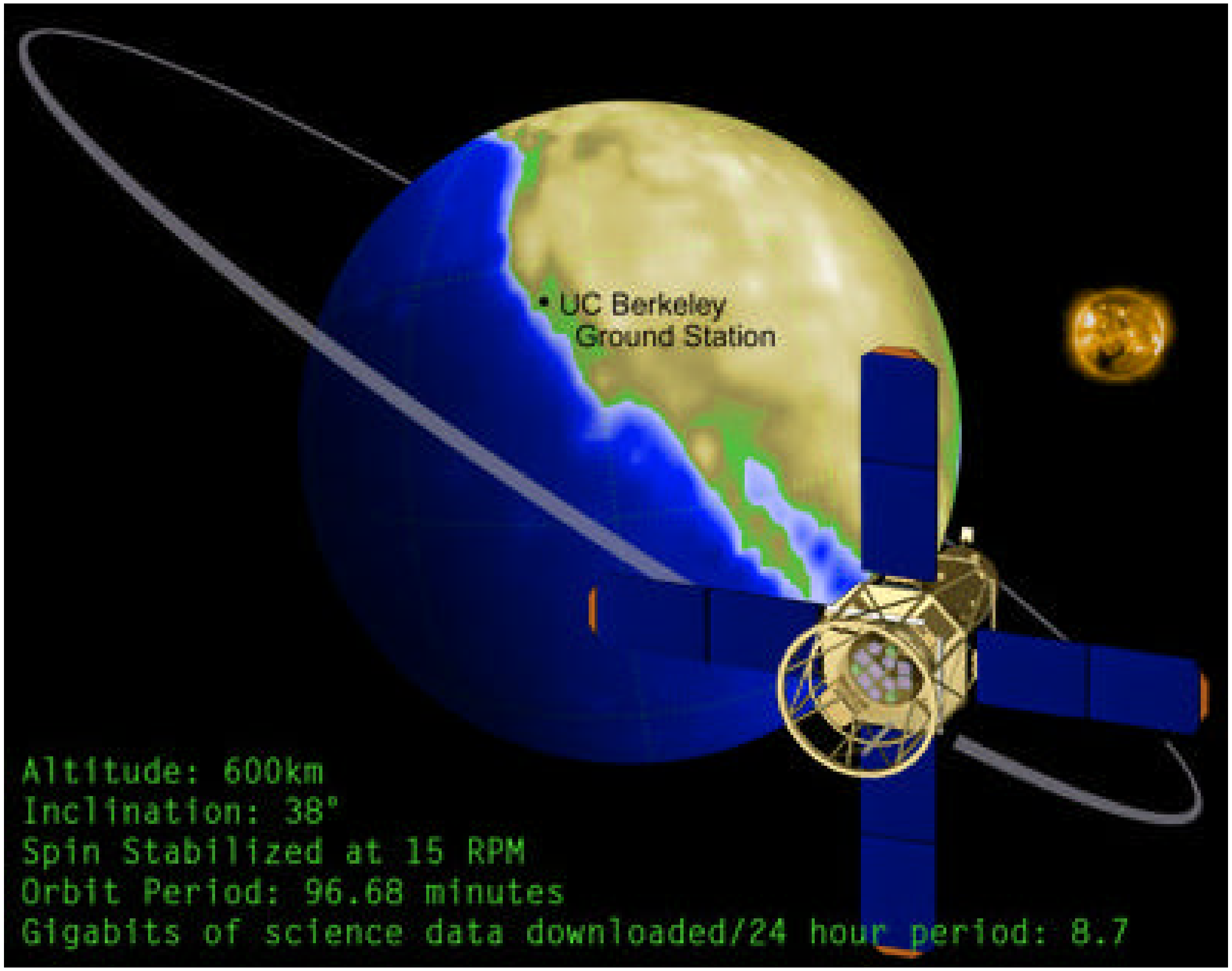


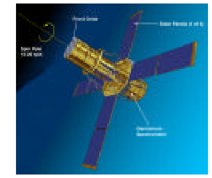
ESTIMATED FLARE RATE



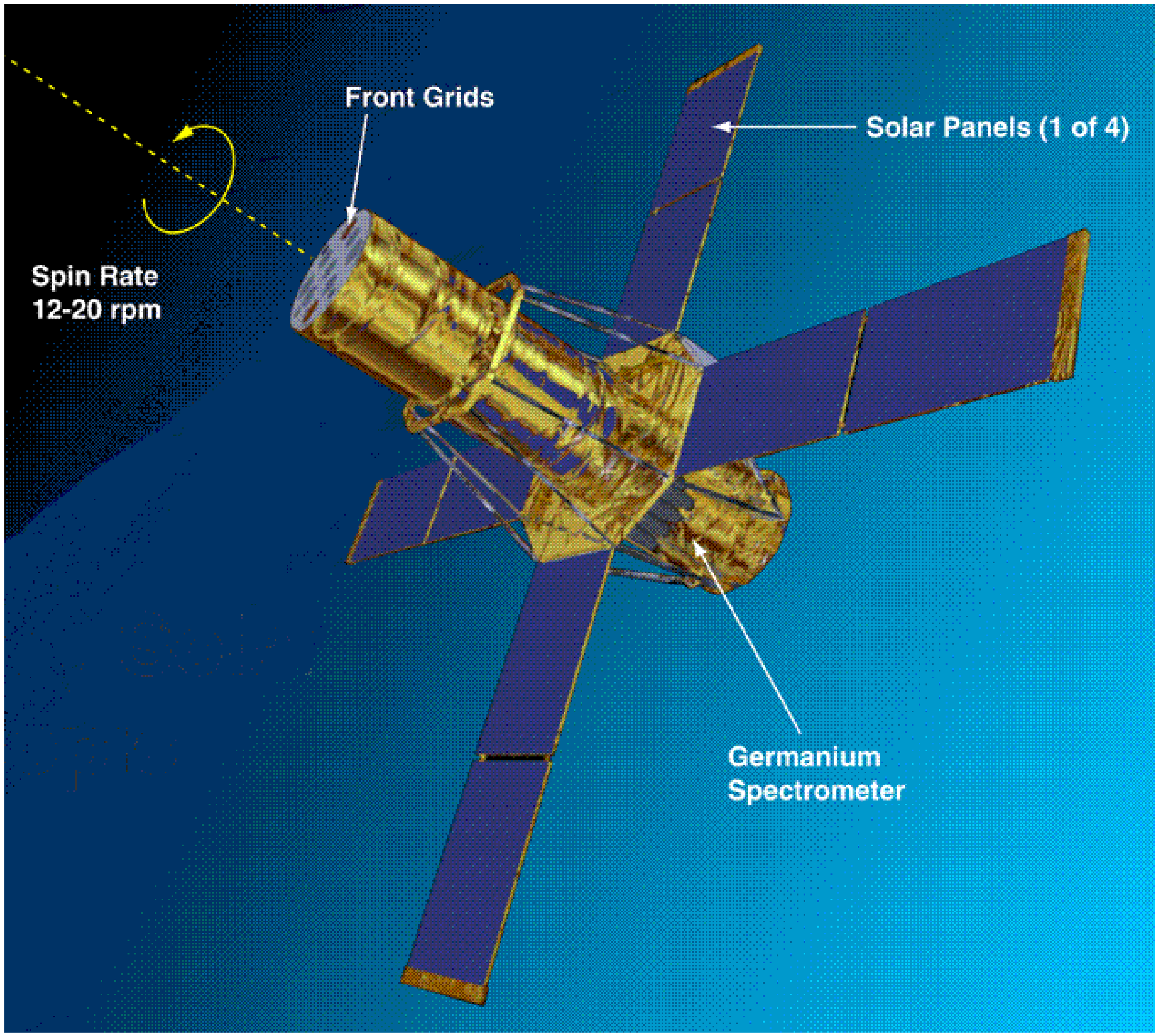


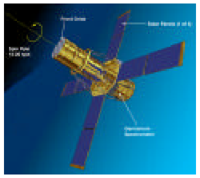
HESSI In Orbit (Launch May/June)



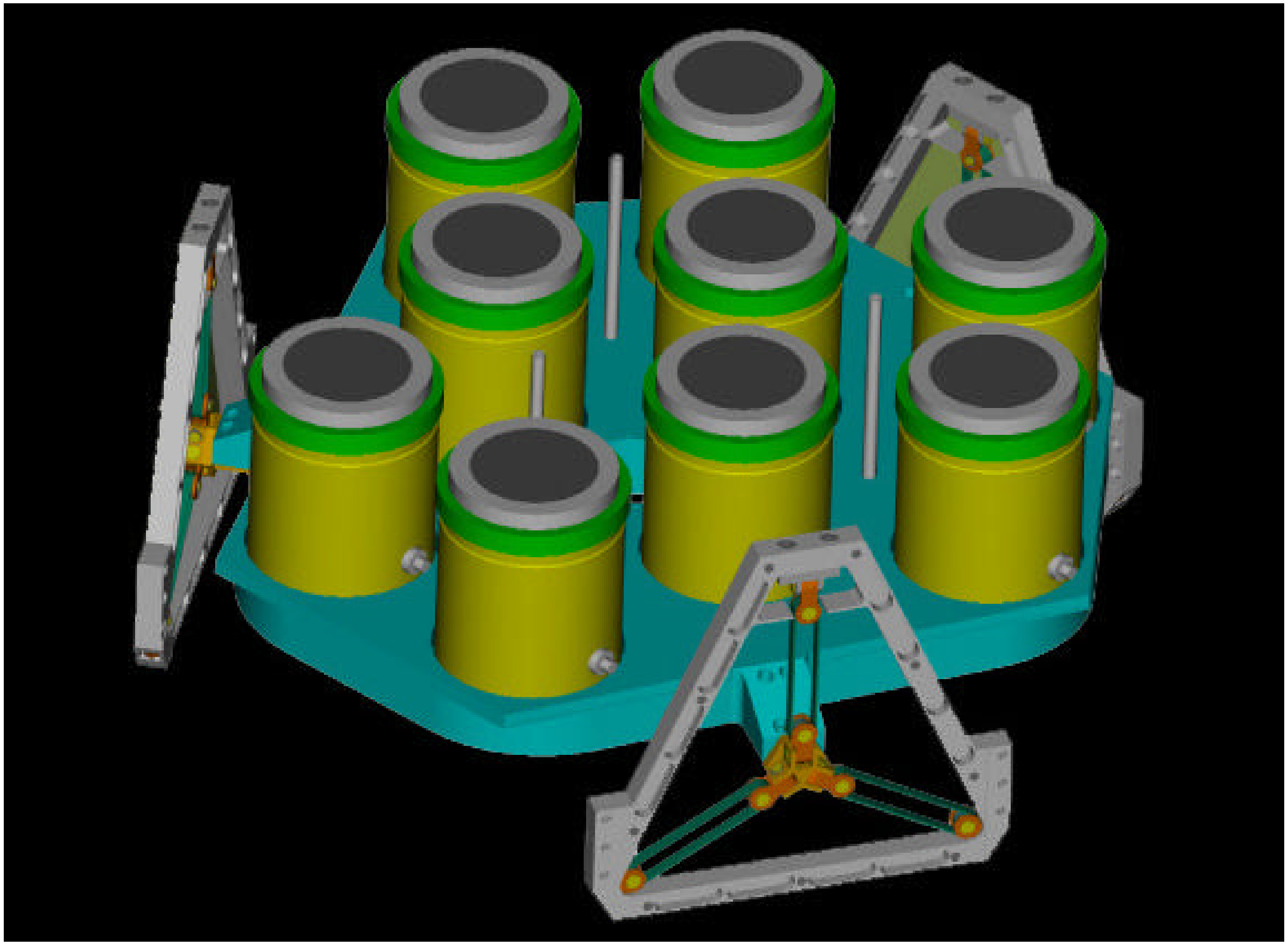


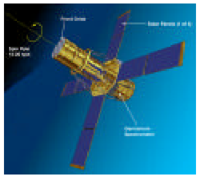
The High Energy Solar Spectroscopic Imager



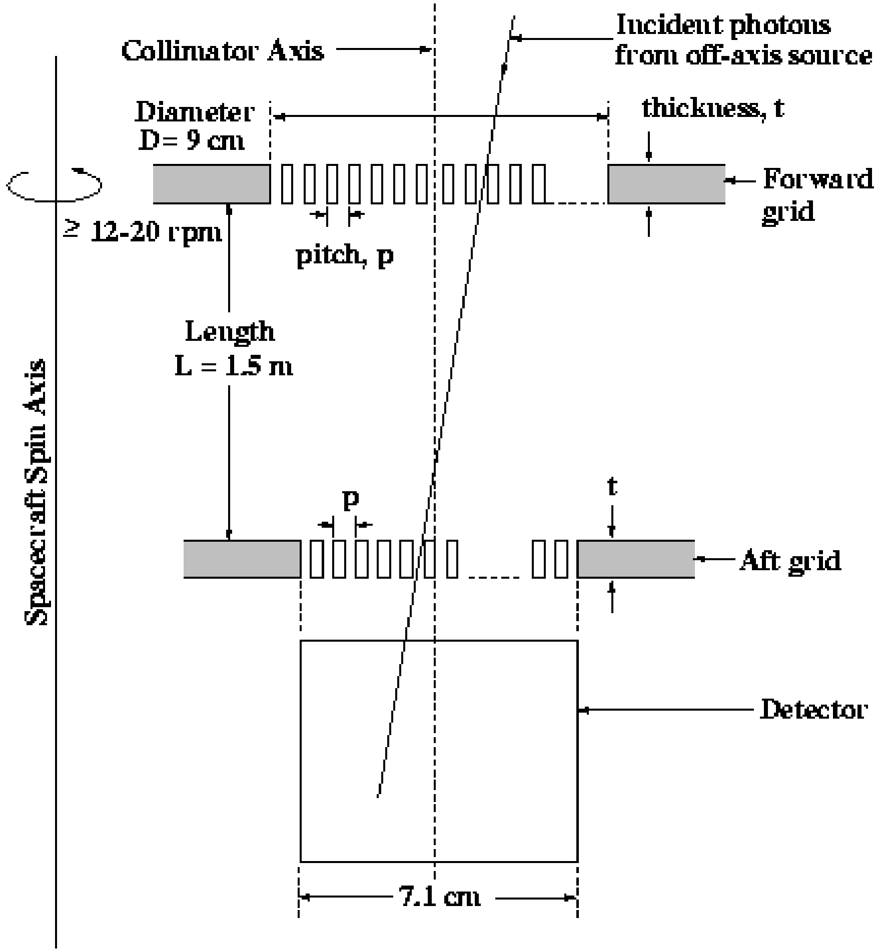


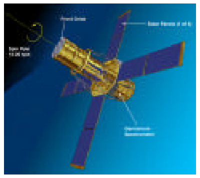
HESSI Germanium Detector Array





HESSI IMAGING SYSTEM





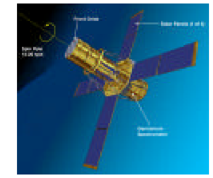
HESSI'S IMAGING/SPECTROSCOPY CAPABILITIES

Energy Range: 3 keV to 400 keV

Angular resolution: 2 to 7 arc sec
Temporal resolution: tens of milliseconds
Energy Resolution: 0.5 keV to 2 keV

Energy Range: 400 keV to 20 MeV

Angular resolution: 7 to 30 arc sec
Energy Resolution: 2 keV to 6 keV



SIMULATED HESSI IMAGES

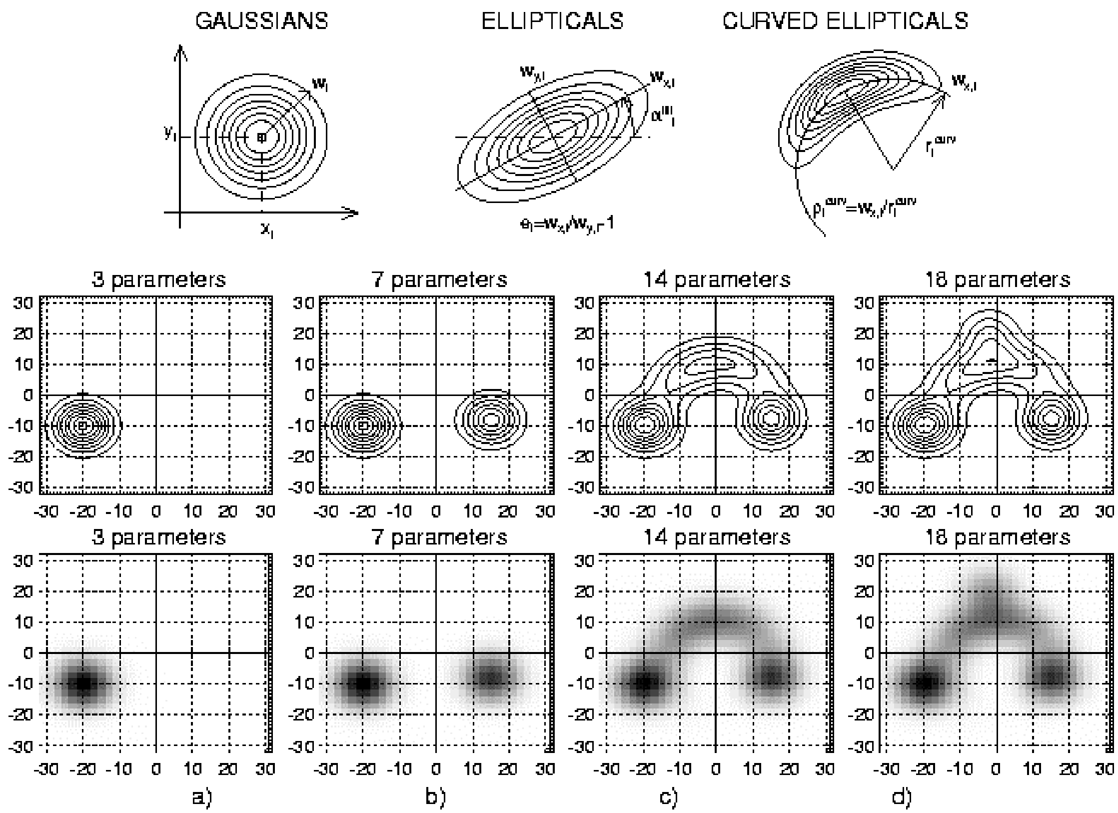


Figure 9 : Aschwanden et al. 2000