Polarization Study of Astronomical Hard X-rays with Well-type Phoswich Compton Polarimeter

Tuneyoshi (Tune) Kamae (SLAC)
for the collaboration
(SLAC-Goddard-Princeton-Japan-Sweden-France)

Introduction

Conceptual Design of the Instrument

Possible Targets of the Instrument

On-Going R/D

Summary

Introduction: Polarization in X-ray astronomy

Photons are characterized by 3 quantities: direction, energy, polarization

- **Direction: Spatial resolution of X-ray instrument**
  - **1978 Einstein: 1 arcmin**
  - **1990 ROSAT: 30 arcsec**
  - **1999 Chandra: 0.3 arcsec**
  - **1999 XMM: 4.3 arcsec**
- **Sensitivity for point source detection of X-ray instrument**
  - **1978 Einstein (survey, 0.2-3.5keV): 10**(-11)erg/cm**2/s**
  - **1990 ROSAT (survey, 0.5-2.5keV): 10**(-13)erg/cm**2/s**
  - **1999 Chandra (100ks, 0.5-2.0keV): 2.3x10**(-16)erg/cm**2/s**
  - **1999 XMM (100ks, 0.1-2.4keV): 2.7x10**(-15)erg/cm**2/s**
- **Energy: Spectral resolution of X-ray instruments**
  - **1999 Chandra: 1-10eV or 1/(100-1000)**
  - **1999 XMM: 1-10eV or 1/(100-800)**
- **Polarization: No measurement since 1975/6 in the X-ray band**
  - **1976 OSO-8: Crab total at 2.6 and 5.2keV**

Crab Polarization Measurements with OSO-8 (1976) (1/5)
by a Columbia group (Weisskopf et al.)

THE ASTROPHYSICAL JOURNAL, 208:L125–L128, 1976 September 15

MEASUREMENT OF THE X-RAY POLARIZATION OF THE CRAB NEBULA

M. C. WEISSKOPF, G. G. COHEN, H. L. KESTENBAUM, K. S. LONG, R. NOVICK, AND R. S. WOLFF
Columbia Astrophysics Laboratory, Columbia University
Received 1976 June 7

ABSTRACT

The graphite crystal X-ray polarimeters aboard the OSO-8 satellite were used to observe the Crab Nebula for six days from 1976 March 11 through March 17 (UT). Analysis of 15 orbits of quick-look data shows that the polarization and position angles at 2.6 and 5.2 keV are (15.7 ± 1.5) percent at 161°.1 ± 2°.8 and (18.3 ± 4.2) percent at 155°.5 ± 6°.6, respectively. These results confirm the previous measurement and the hypothesis of synchrotron X-ray emission.
Subject headings: nebulae: Crab Nebula — polarization — X-rays: sources

A PRECISION MEASUREMENT OF THE X-RAY POLARIZATION OF THE CRAB NEBULA WITHOUT PULSAR CONTAMINATION

M. C. WEISSKOPF, E. H. SILVER, H. L. KESTENBAUM, K. S. LONG, AND R. NOVICK
Columbia Astrophysics Laboratory, Columbia University
Received 1977 November 15; accepted 1977 December 22

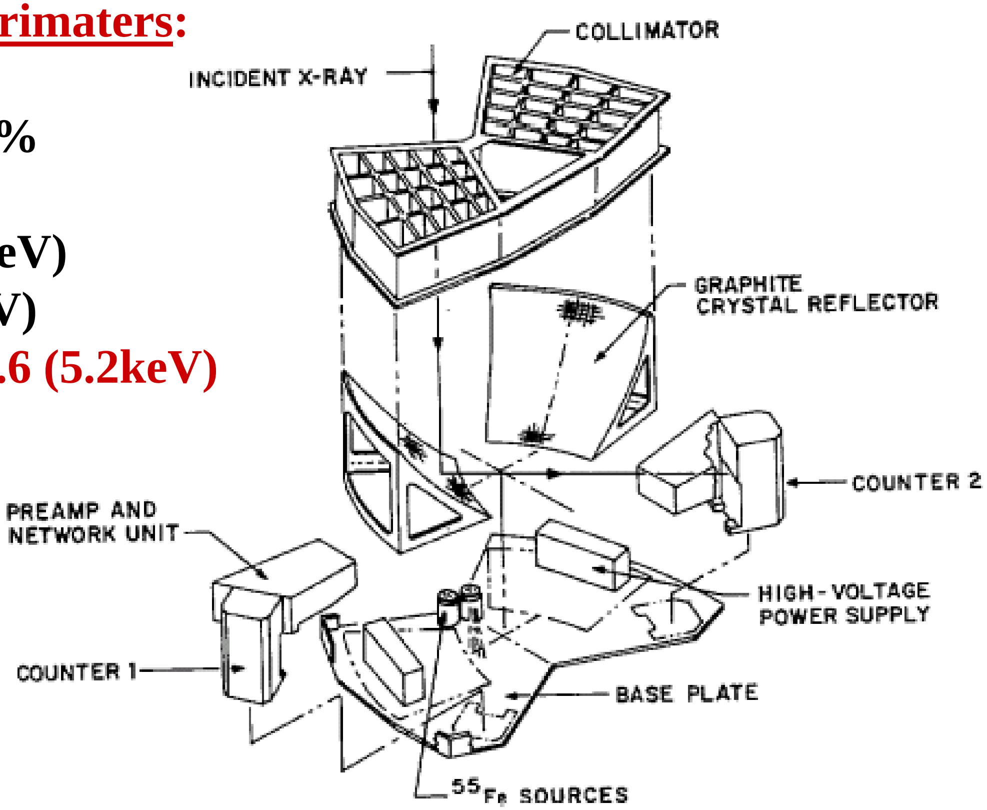
ABSTRACT

The linear X-ray polarization of the Crab Nebula has been precisely measured at 2.6 keV and 5.2 keV with the *OSO* 8 graphite crystal polarimeters. The 1.4 ms time resolution of these instruments permitted the removal of any contribution to the polarization from the pulsar. The nebular polarization is 19.2% ± 1.0% at a position angle of 156°.4 ± 1°.4 at 2.6 keV. At 5.2 keV the corresponding results are 19.5% ± 2.8% at 152°.6 ± 4°.0.
Subject headings: nebulae: Crab Nebula — polarization

Crab Polarization Measurements with OSO-8 (1976) (2/5)
by a Columbia group (Weisskopf et al.)

Two Carbon Bragg diffr. Polarimaters:

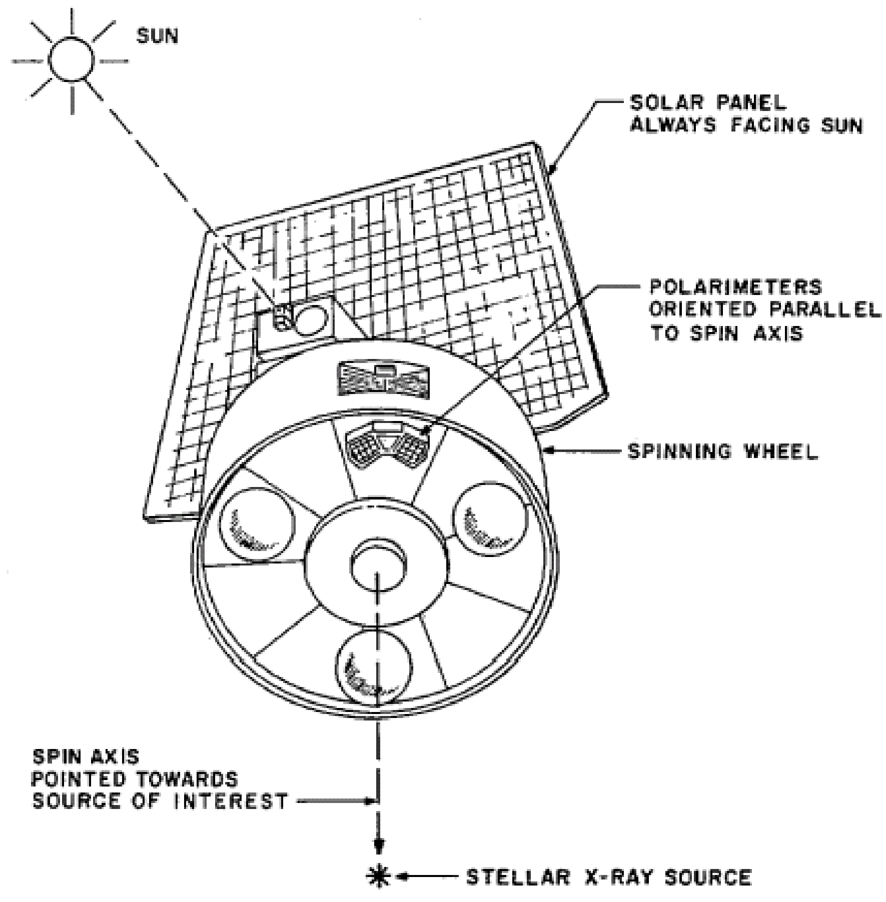
Mod factor for 100% pol = 94%
Count rate = 3.8kHz (2.6keV)
= 0.7-0.9kHz (5.2keV)
S/N = ~10 (2.6keV), ~2 (5.2keV)
Pol x S/N = 1-2 (2.6keV), 0.2-0.6 (5.2keV)
Total obs. Time = 71.2 hrs



Crab Polarization Measurements with OSO-8 (1976) (3/5)
by a Columbia group (Weisskopf et al.)

<u>Rotating wheel:</u>

Minimize possible systematic bias



Crab Polarization Measurements with OSO-8 (1976) (4/5)

by a Columbia group (Weisskopf et al.)

L118 WEISSKOPF *ET AL.*

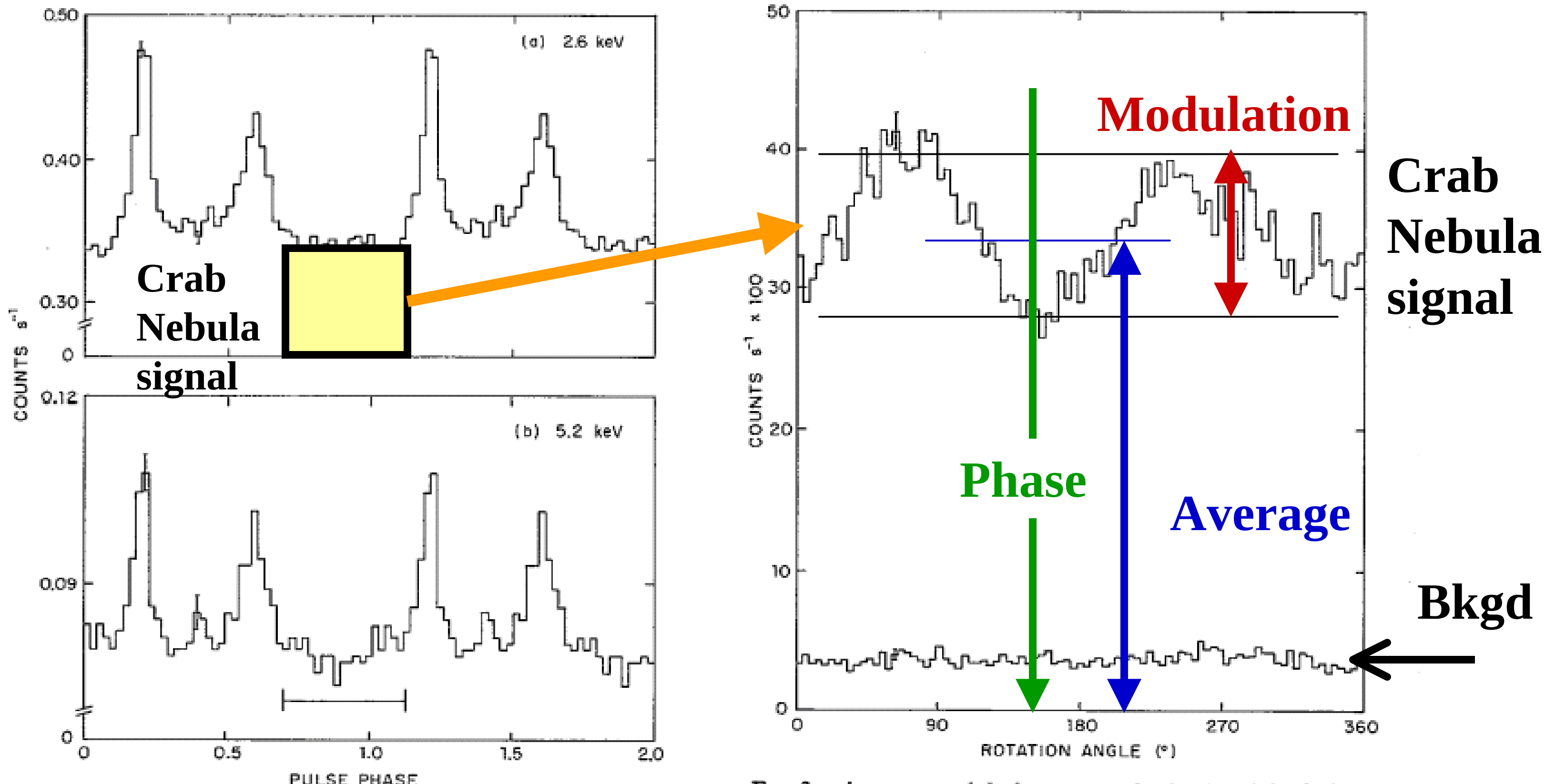


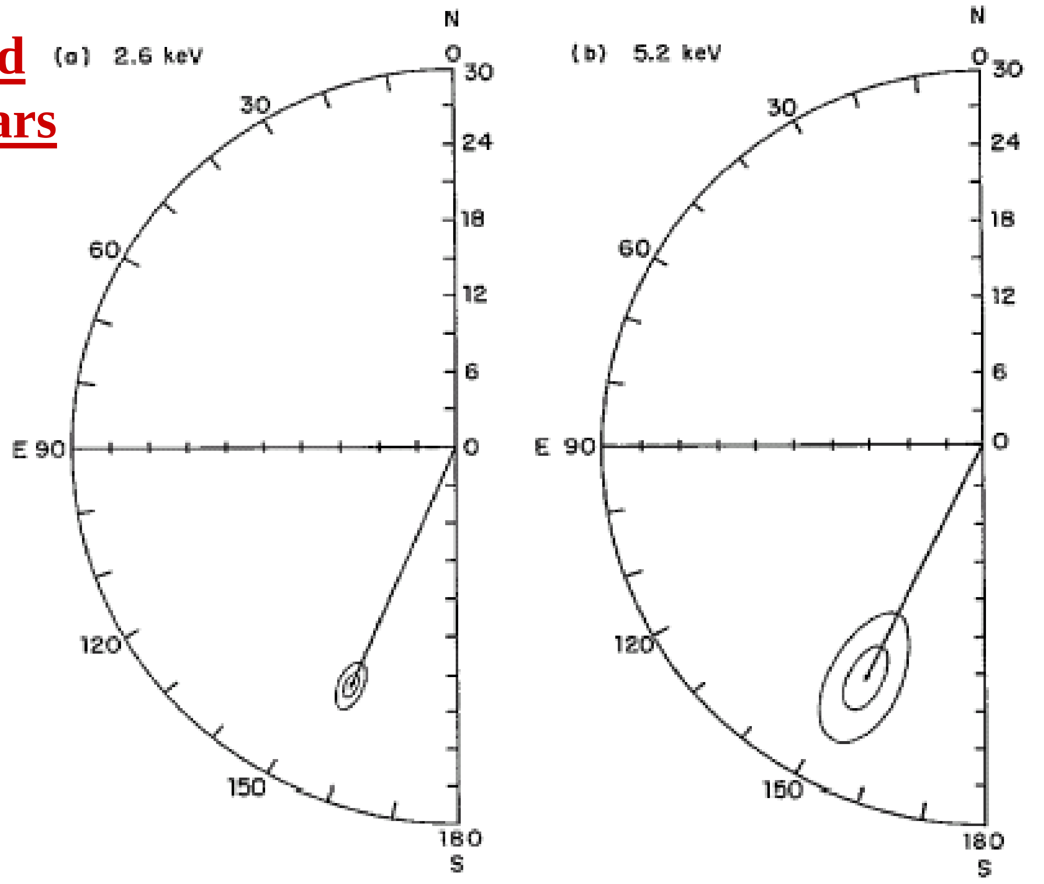
FIG. 1.—Crab pulsar light curves for (*a*) first-order (2.6 keV) and (*b*) second-order (5.2 keV) Bragg reflections. The horizontal bar in each light curve indicates the unpulsed portion of the light curve.

FIG. 2.—Average modulation curves obtained with both detectors at 2.6 keV during (*upper curve*) observations of the Crab Nebula and during (*lower curve*) observations of the Earth-occulted instrumental background.

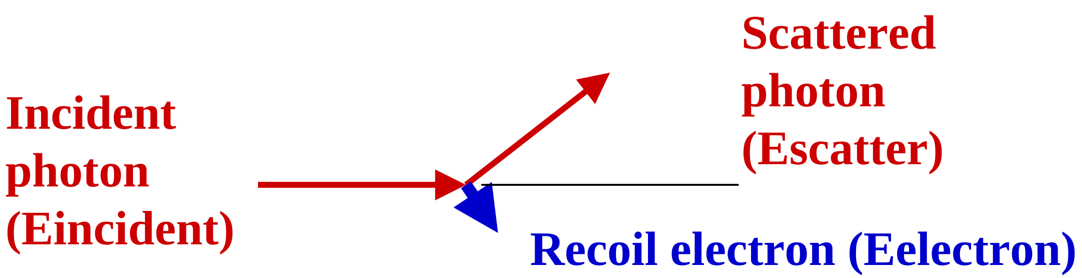
Crab Polarization Measurements with OSO-8 (1976) (5/5)

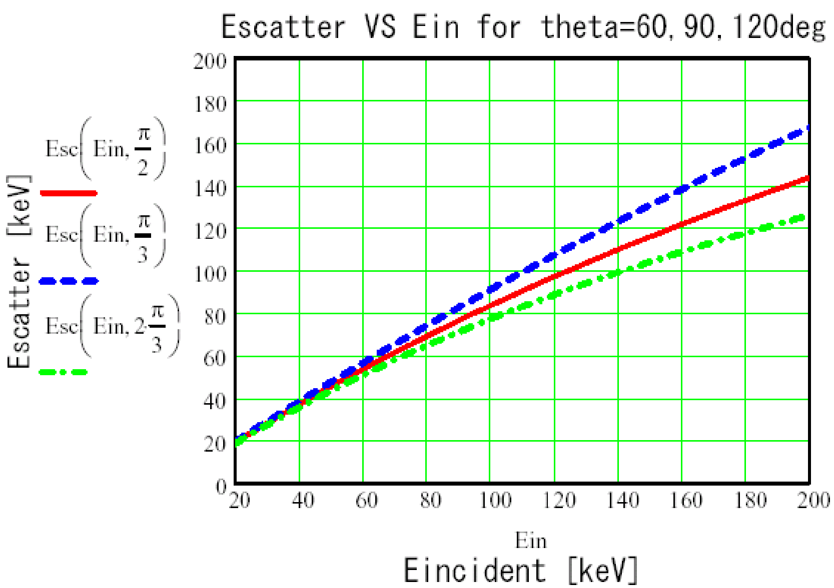
by a Columbia group (Weisskopf et al.)

Results no one could supercede for 27years

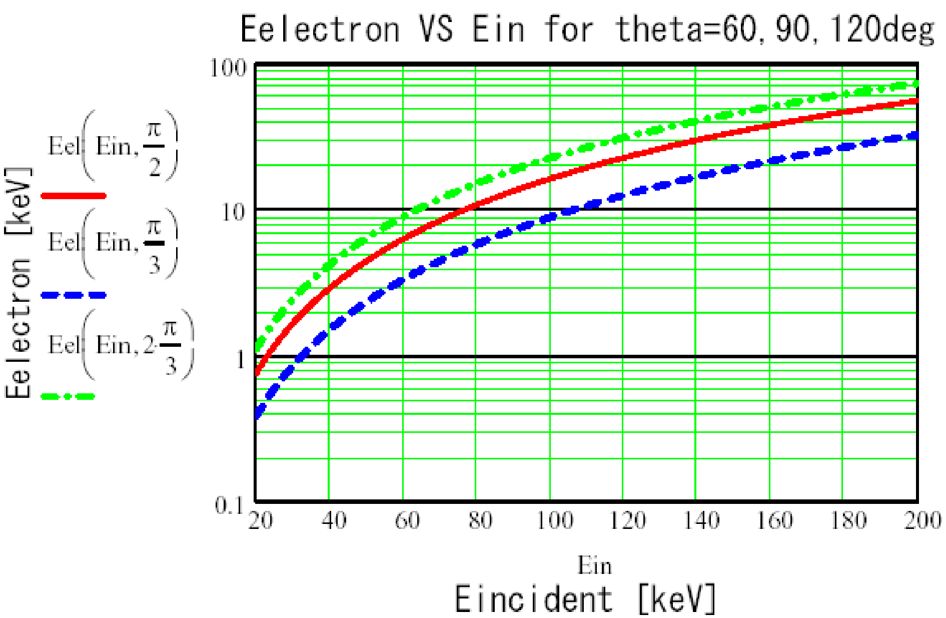


Introduction: Compton scattering kinematics





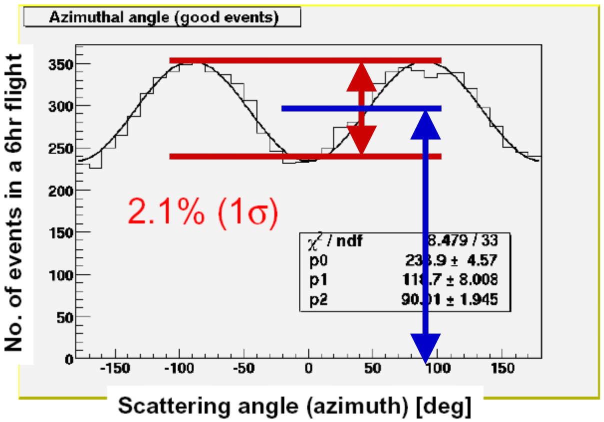
Energy of the scattered photon as a function of the incident energy for theta=60(blue dash), 90(red solid), 120deg(green dot-dash).



Energy of the recoil electron vs. the incident energy for the 3 theta's.

Introduction: Modulation factor of Compton scatt.

Modulation factor
=difference/average



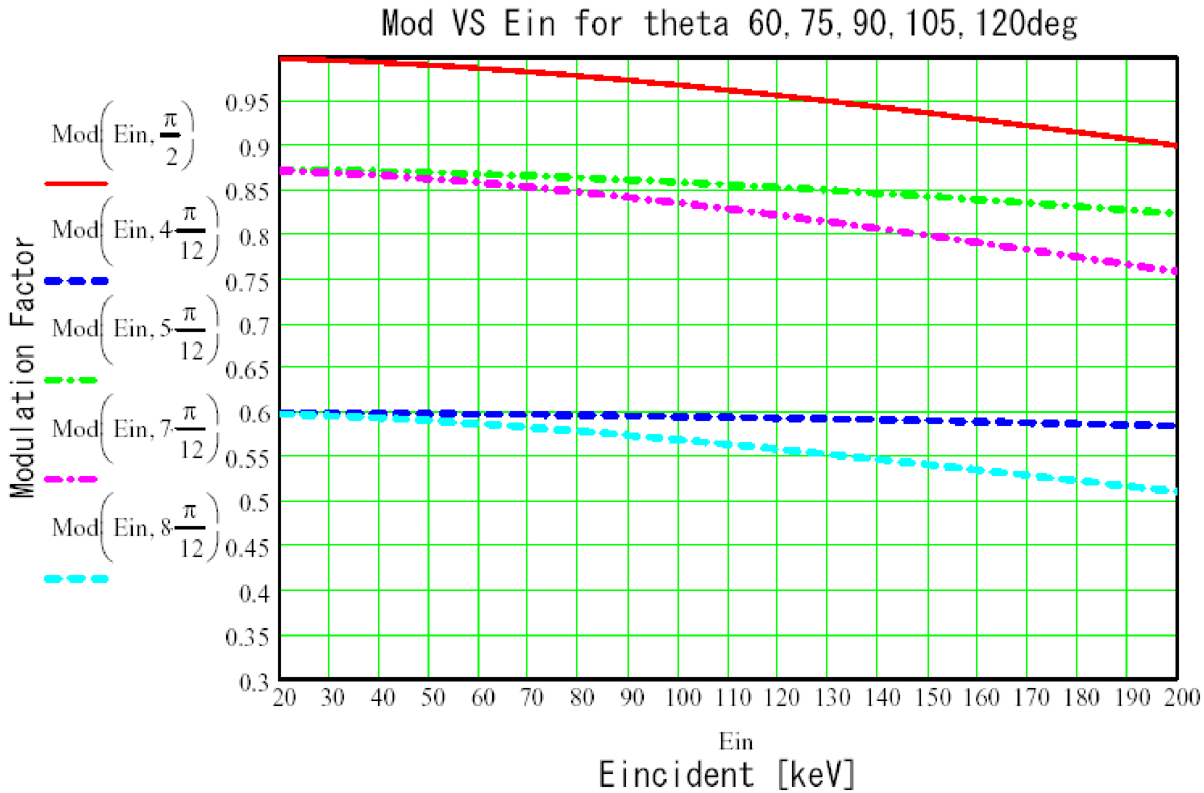


Fig.5-3 Modulation factor of Compton scattering vs. the incident energy: scattering angle (theta)=60deg(blue dash), 75deg(green dot-dash), 90deg(red solid), 105deg(purple dot-dash), 120deg(magenta dash).

Introduction: Key parameters of the instrument

"Sample Design":

- **Measure 10% pol of 100mCrab sources in one 6hr balloon experiment**
- **Reach highest altitude practical to extend energy range to 20keV**
- **Reduction of background to ~10mCrab level**
- **Plastic scintillator as the Compton scatter**

Energy band	25-200keV
Geometric area	1787cm**2
Effective area for pol measurement (average)	288cm**2
Instrumental background (at 50keV)	~10mCrab
Modulation factor for 100% polarized X-rays	36%
Sensitivity to polarization (1sigma)	2.1%

Introduction: Processes known to polarize hard X-rays

- **Synchrotron process**: Electrical vector is perpendicular to the magnetic field and hence polarization measurement determines the direction of magnetic field.
- **Re-scattered via Compton scattering:** Electric vector is perpendicular to the plane of scattering and hence polarization measurement determines the geometrical relation between the photon source and the scatterer.
- **Propagation of photons in strong magnetic field:** Magnitude of polarization depends on the energy of photons. Photons with electric vector perpendicular to the magnetic field are highly absorbed and hence polarization measurement determines the direction and magnitude of the magnetic field.
- **In many astronomical objects, these potentially polarizing processes coexist with other processes.**

Introduction: Polarized X-rays sources

- **Super-massive black holes** where matter accretion powers relativistic jets, accelerates particles, and emits photons via **synchrotron** and **inverse-Compton** mechanisms;
- **Galactic X-ray binaries** where matter accretes onto a black hole or a neutron star and emits hard X-rays. **Inverse-Compton** reflection off the accretion disk polarizes hard X-rays. **Micro-quasars** belong to this category, where the accretion is likely to be powering stellar-scale relativistic jets;
- **Active galaxies** where isotropic emission is scattered toward the Earth by **inverse-Compton** scattering;
- **Accreting neutron stars** with strong **cyclotron line features**;
- Hard X-ray emission from **Soft Gamma-ray Repeaters** with super-critical magnetic fields;
- **Isolated pulsars** with **strong magnetic field**;
- **Ordinary galaxies** (including our own) with extended **inverse Compton** halo;
- **Solar flares and coronae**.

Conceptual Design of the Instrument

- Photoelectron asymm vs. Compton scatt. -

	Photoelectron asymm	Compton scattering
Energy range	3.5 - 10keV	20 - 200 keV
Good S/N by	•X-ray mirror •Fine tracking	•Active shield •Coarse segmentation
Main bkg	•Thermal emission from the source	•Source confusion in FOV •Cosmic ray background
Mod factor	~40%	~40-80%
Platform	Satellite	Balloon Satellite
Merit	•Fine imaging	•Optimal to pol. processes •Simple and robust •Cost-effective
Demerit	•Require intensive care •Heavy on data processing	•No image

Conceptual Design of the Instrument

- Basic strategy -

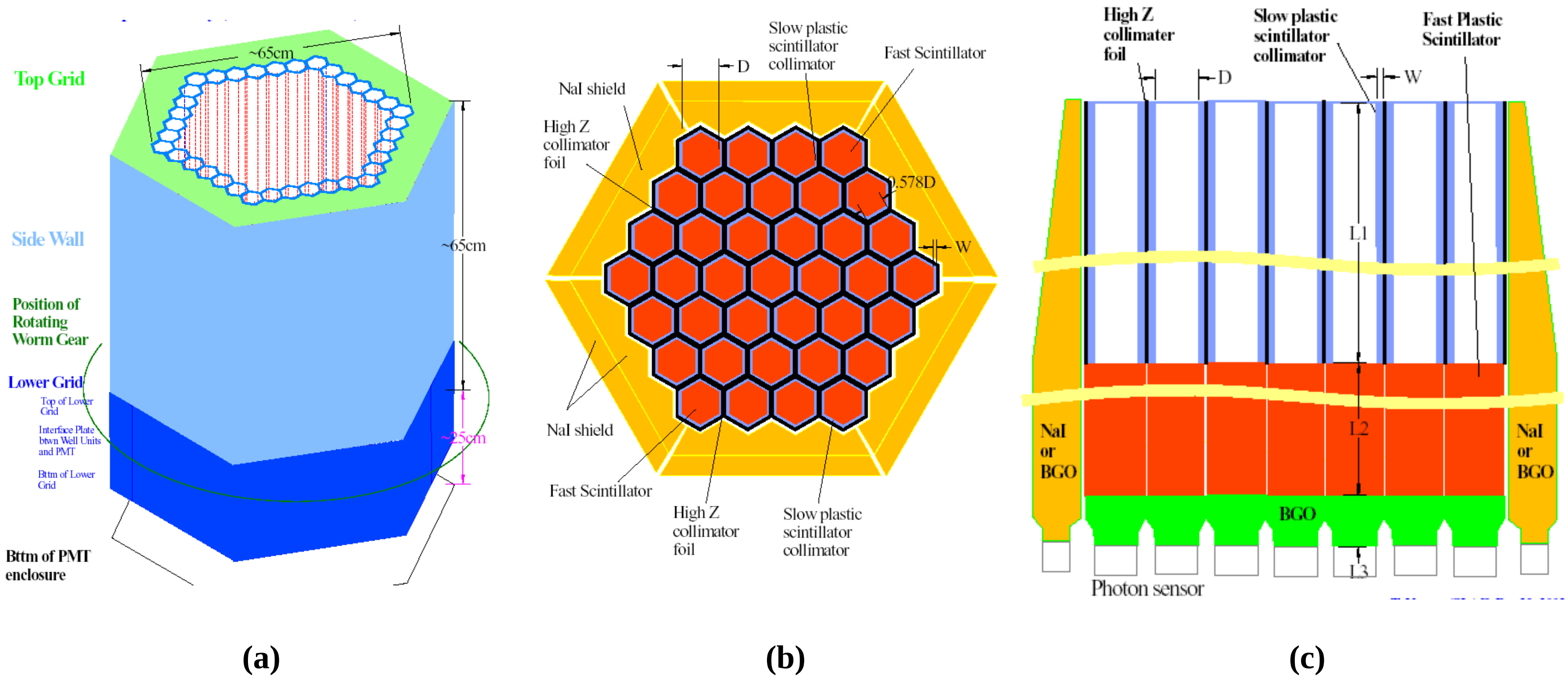
Fig. of merit = Expected modulation factor x Expected S/N

From the pioneering experiment by Weisskopf et al., we learn that the fig. of merit defined above must be >>1 to make a reliable measurements. This implies:

- Maximize modulation factor
- Maximize S/N ratio
- Fly high (>45km) to extend the energy coverage as low as possible
- Service-free instrument to stay ready upon flare alerts

- Maximizing effective area is less important than the above.

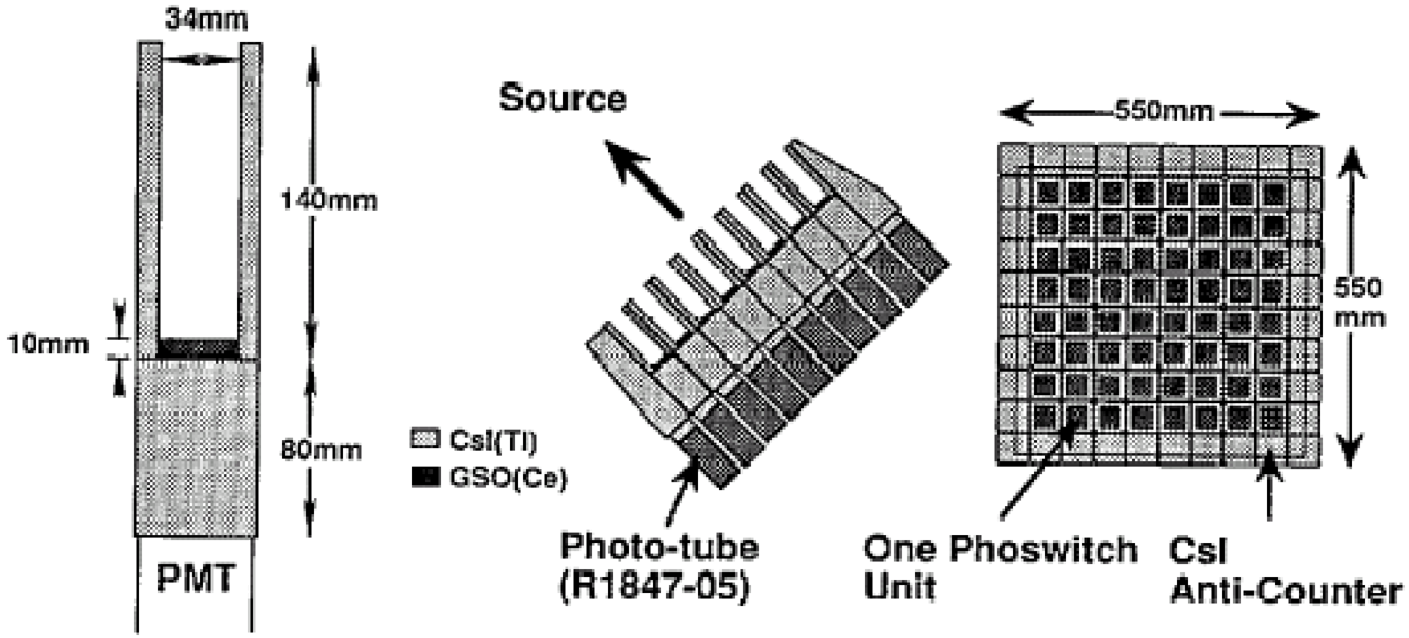
Conceptual Design of the Instrument: No.1



Conceptual design of the instrument (number of units will be greater than shown here): a) Isometric view; (b) View from the front of the instrument; (c) Vertical cross-section of the instrument. The proposed instrument will have ~400 units and L1 + L2 in (c) will be ~60cm.

Heritage from Welcome-1 and Astro-E HXD (1/2)

Heritage from the balloon instrument Welcome-1 flown 4 times in Brazil



(a) Well-type Phoswich Counter (First model)

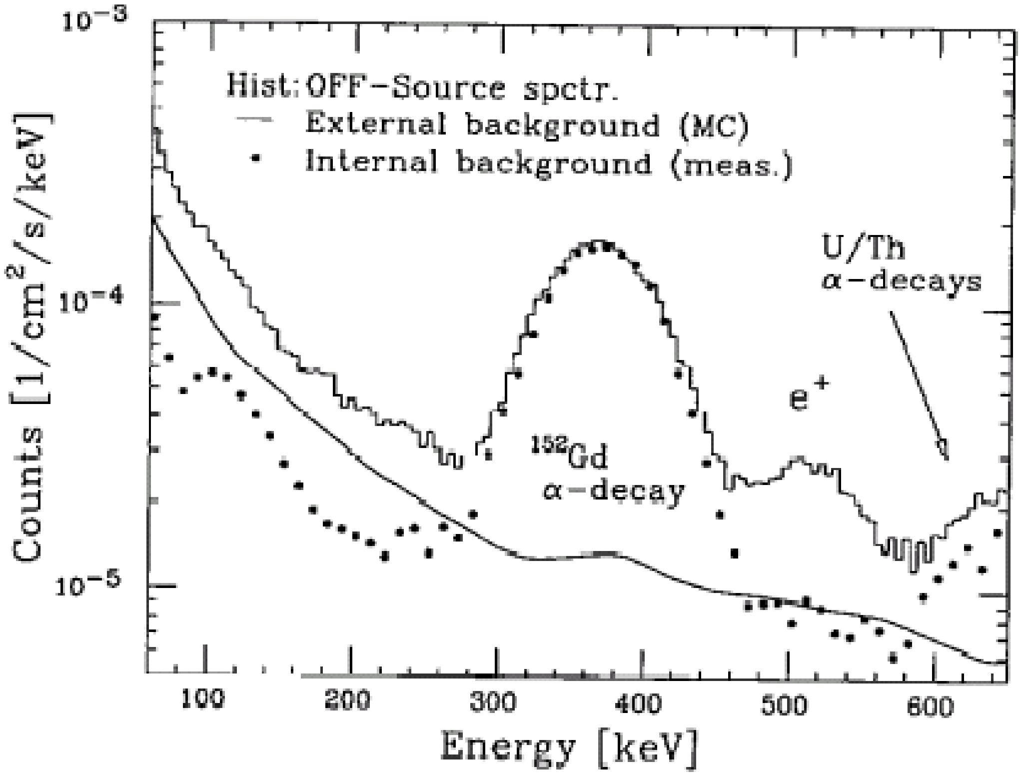
(b) Compound-Eye Configuration Detector "Welcome-1"

Heritage: from Welcome-1 and Astro-E HXD

Lowest background ever achieved in the hard X-ray band

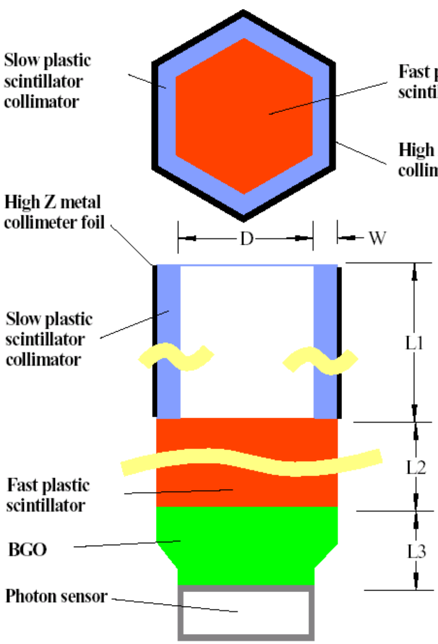
Welcome-1:
A series of balloon experiments in Brazil

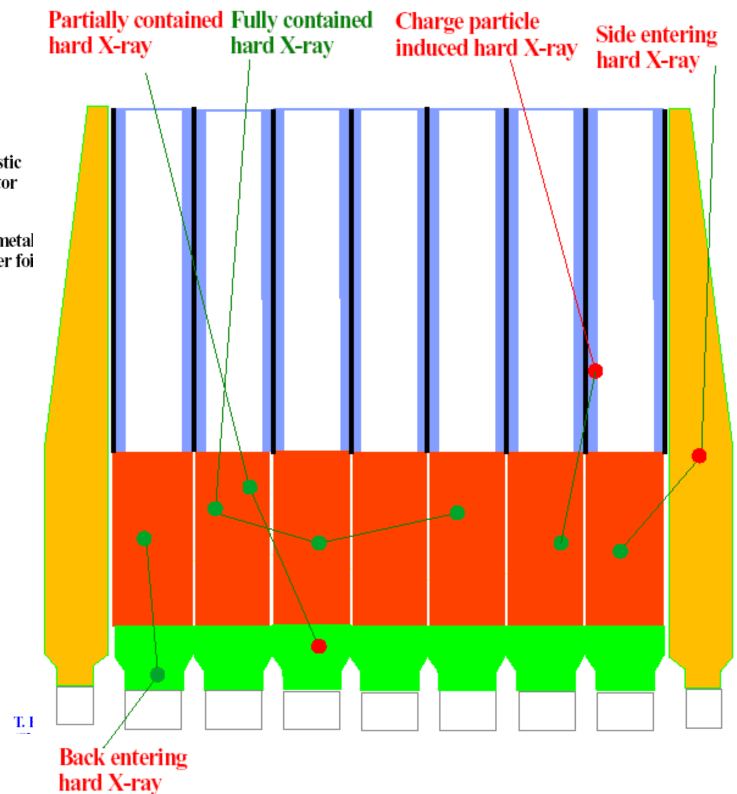
- **Upper limit to Co57 from SN1997A**
- **First detection in hard X-ray of PSR 1509**
- **Detection of H.E. cutoff of CenA**
- **First detection of inv. Compton component in high latitude Galactic diffuse emission**

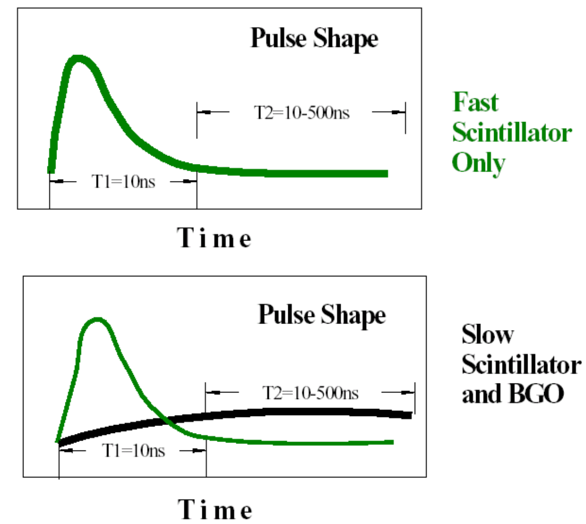


Conceptual Design of the Instrument: No.2

Trigger and Pulse-Shape-Discrimination

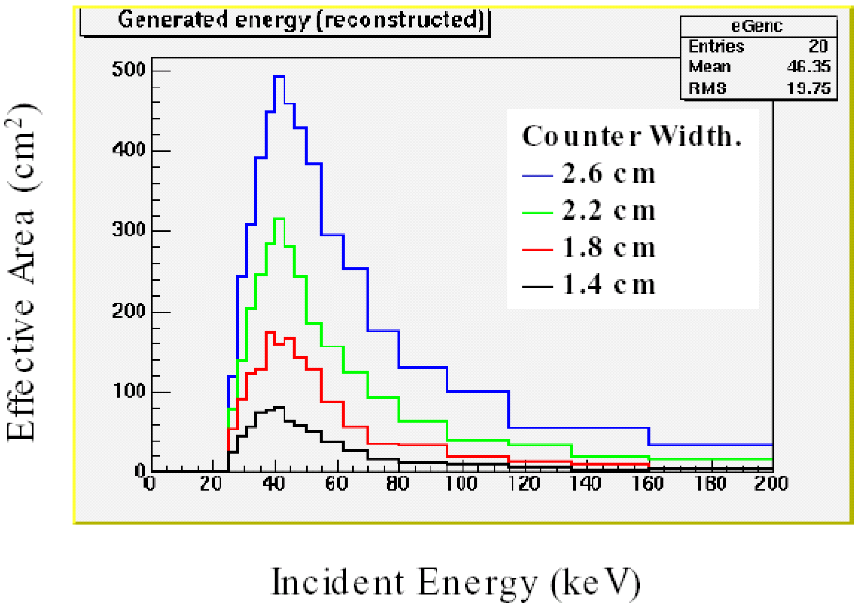




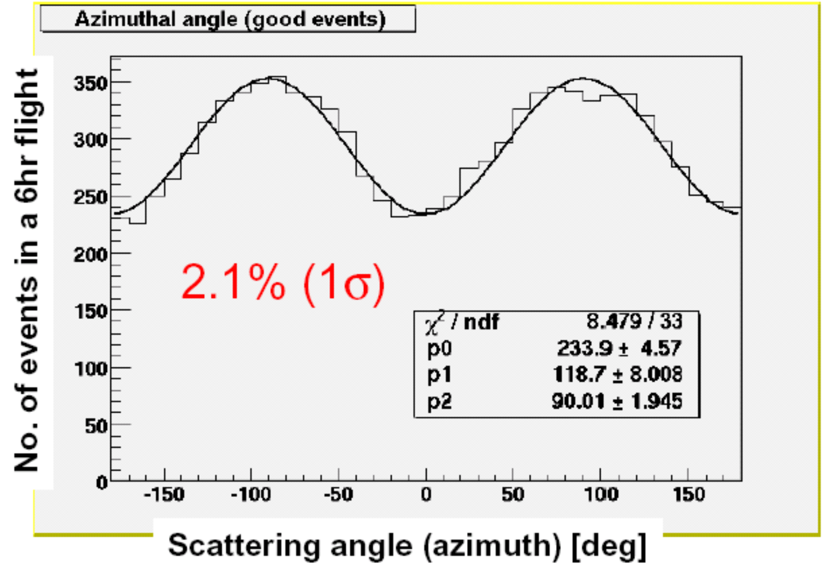


Conceptual Design of the Instrument: No.3

Effective area and modulation factor

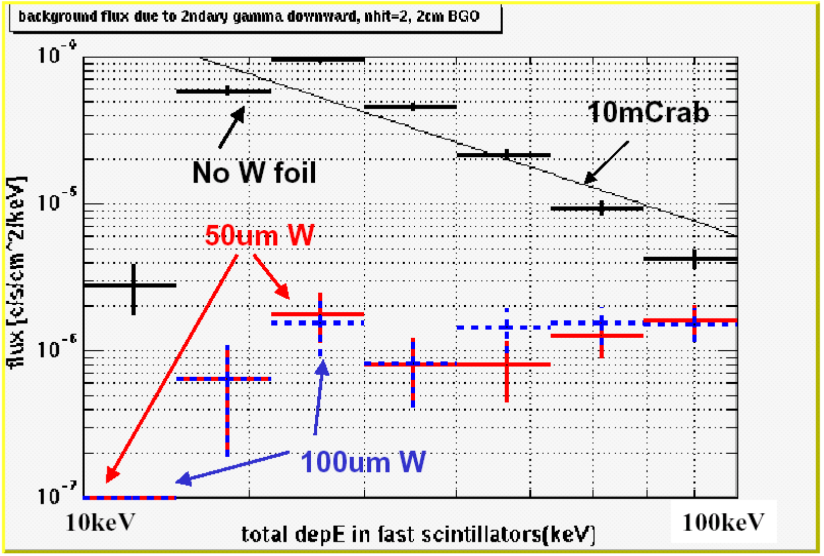


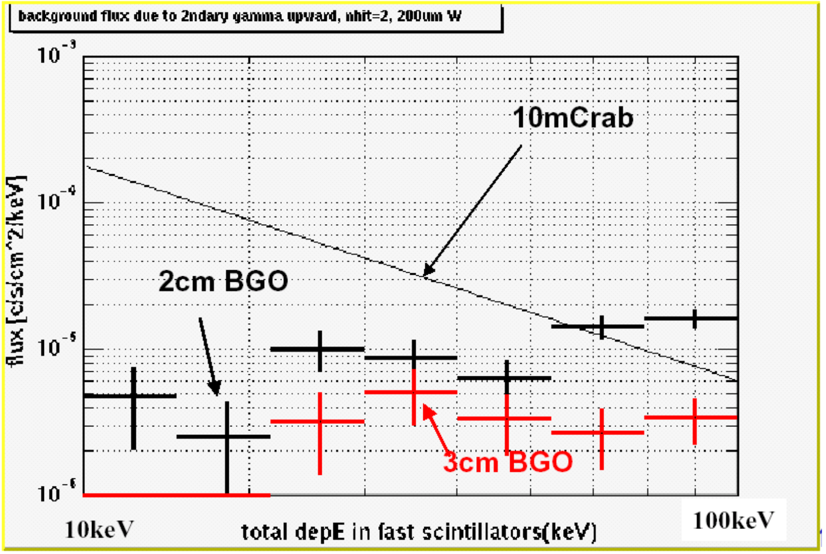
36% averaged over 100mCrab flux over 25-200keV



Conceptual Design of the Instrument: No.4

Background will be quite low: 1/10 of Welcome-1





“Sample Design” of the Instrument

Detector Parameters	Choices
Width of Well Unit: D in Fig.5-1	**2.68cm** by compromise btwn effective area and cost (Fig.3-4)
Length of fast plastic scintillator: L2 in Fig.5-1	**15-20cm** by photon yield and weight
Length of slow plastic scintillator: L1 in Fig.5-1	**40cm** by req. for background & source confusion
Material and thickness of High-Z Foil	**Pb** (cheap and flexible), **50um** (see Fig.5-4)
Thickness of BGO: L3 in Fig.5-1	**3cm** by by requirement for background (see Fig.5-4)
Material and thickness of Anti-Counters	**BGO**, **3cm** (see Fig.5-4)
Number of Well Units	**397** compromise among effective area, weight, and cost
PMT: New hex PMT or existing circular PMT	Compromise between photo-electron yield and cost

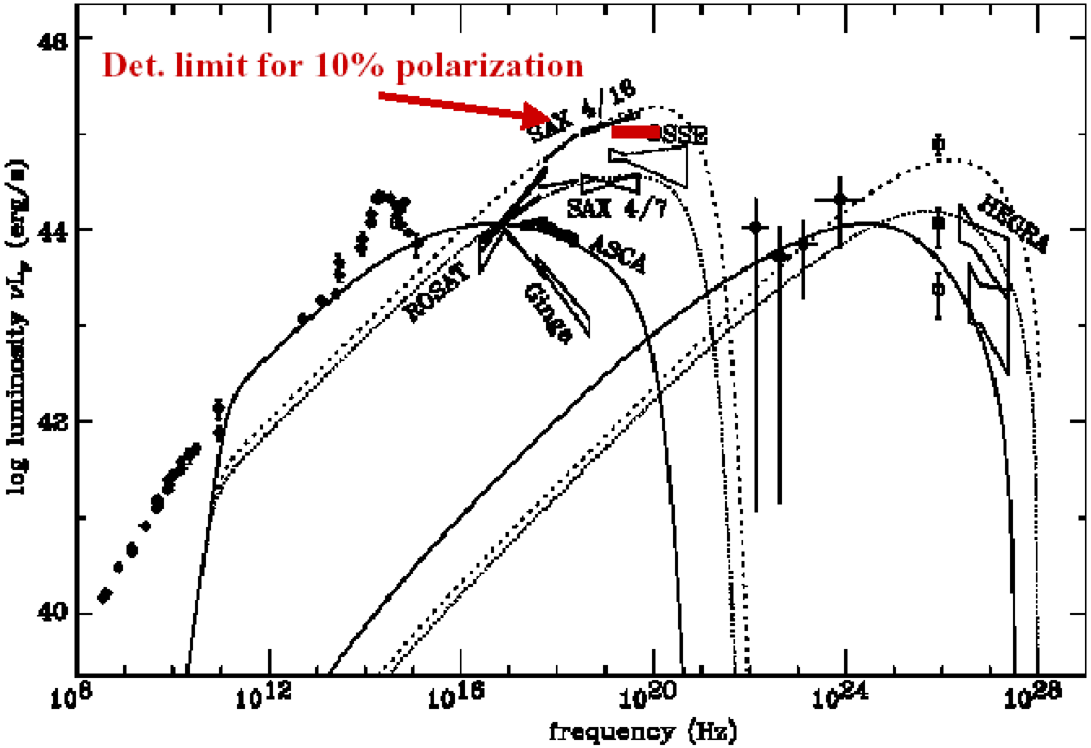
Possible Targets of the Instrument: No.1

Jet-dominated active galaxies

High Frequency Peak BL Lac Objects (HBL)

Flares last ~1-2 weeks.
Need notification by a survey mission, eg. GLAST-LAT

Mrk 501 in flaring states

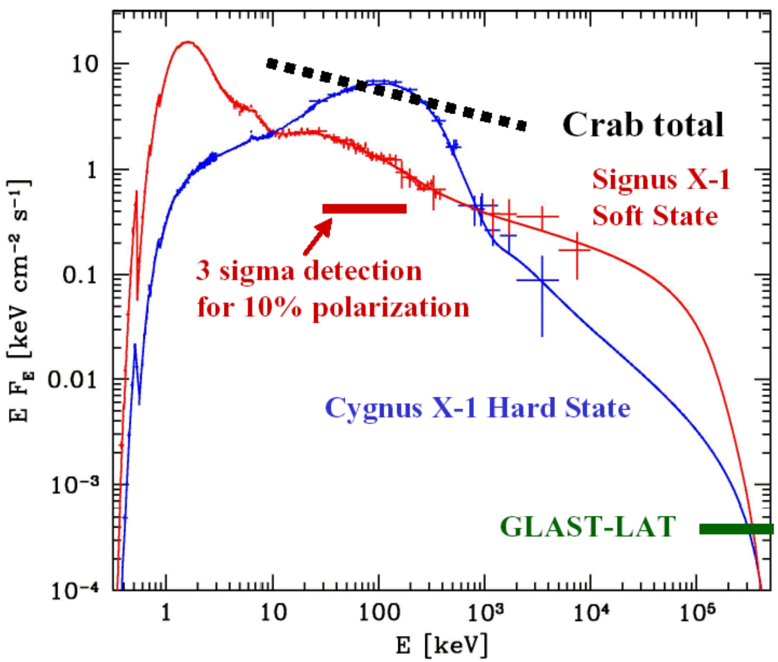


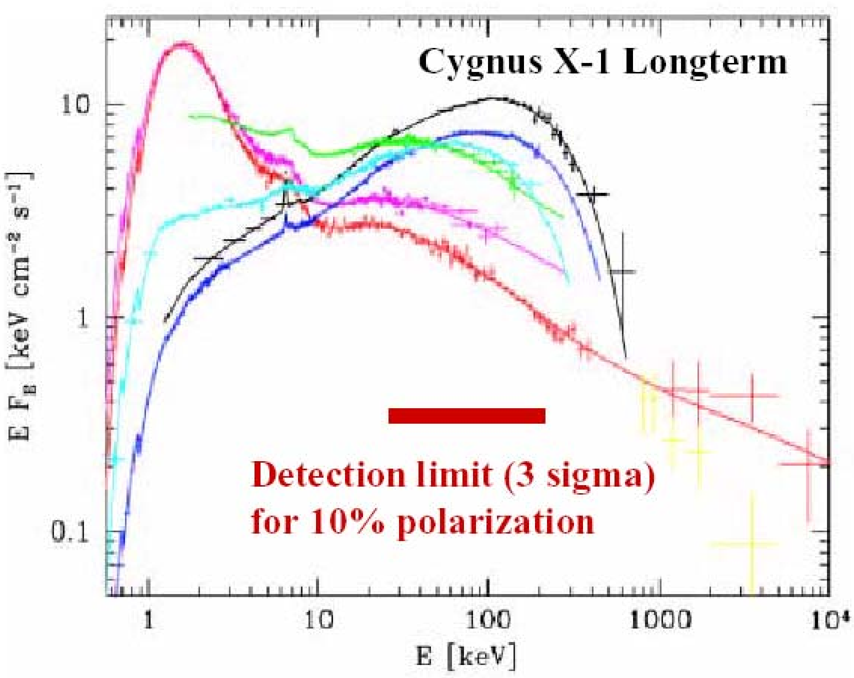
Possible Targets of the Instrument: No.2

Accreting Galactic Black Holes and Neutron Stars

Accreting black hole in hard state

Cygnus X-1 hard state: stays in the hard state for a few months to a few years



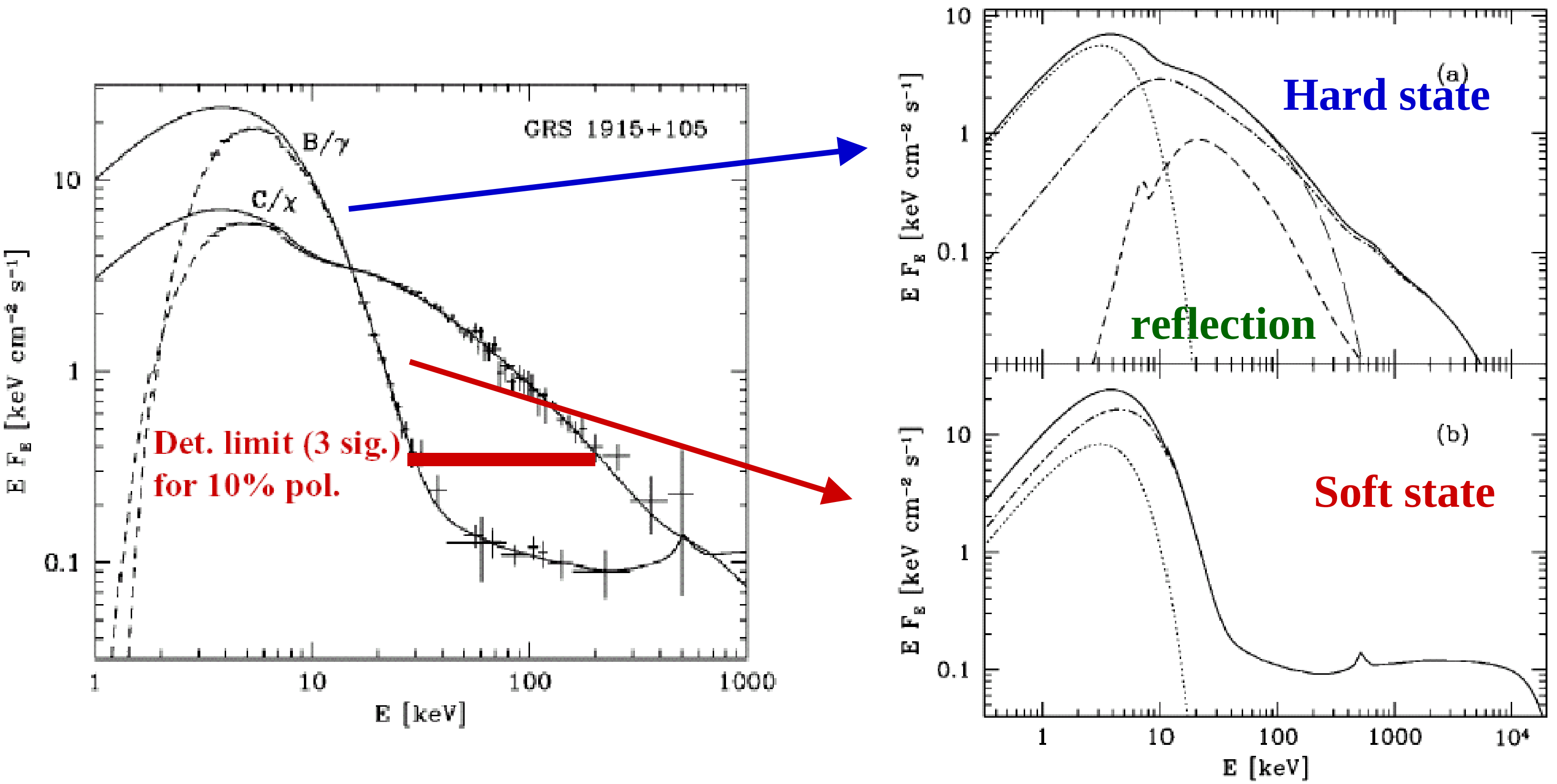


Possible Targets of the Instrument: No.3

Accreting Galactic Black Holes and Neutron Stars

Microquasar in hard state

Model analysis by Zdziarski et al.

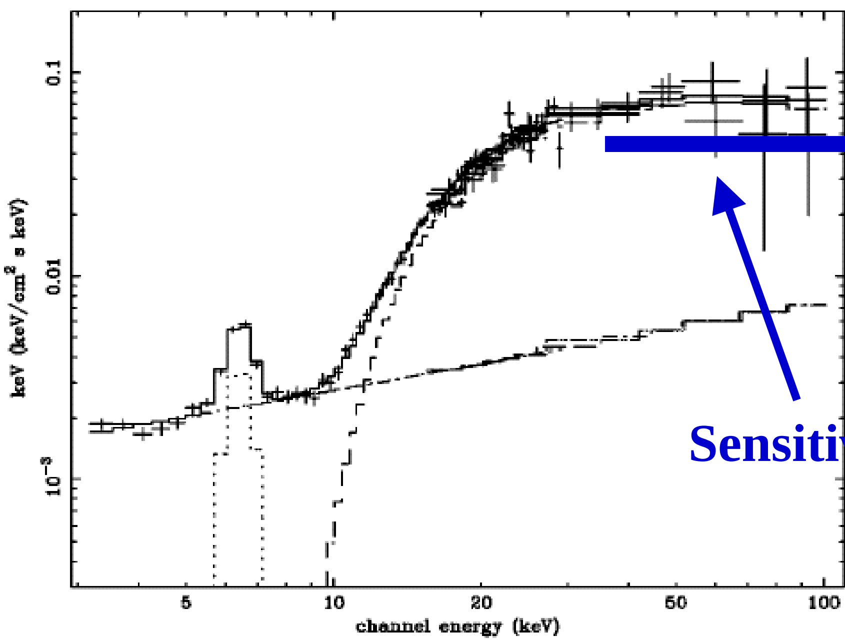


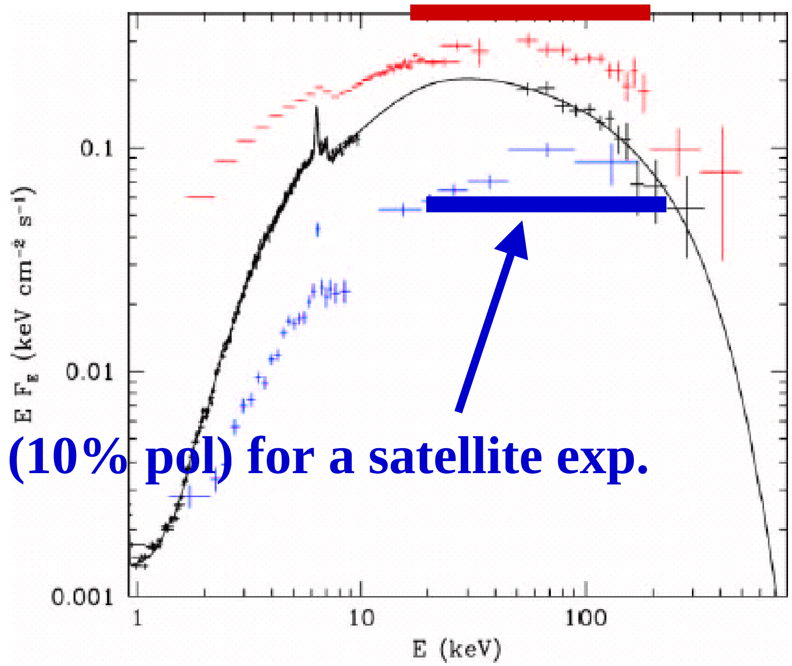
Possible Targets of the Instrument: No.4

Isotropic emission from AGN

Compton reflection of the hidden central engine

Sensitivity (10% pol) for a balloon exp.





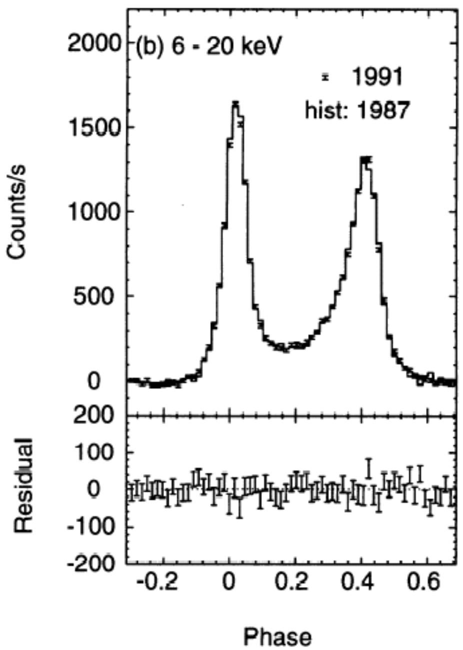
Sensitivity (10% pol) for a satellite exp.

NGC4945 **NGC4151**

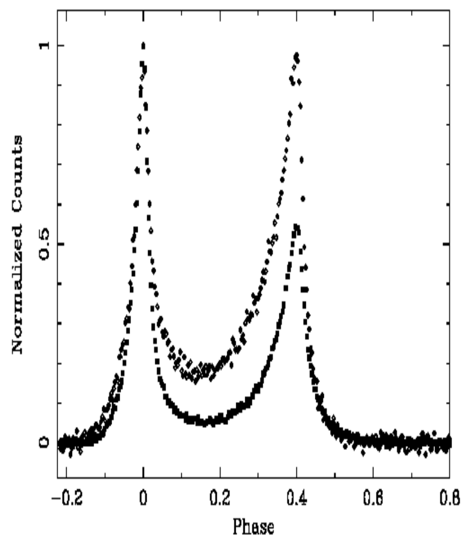
Possible Targets of the Instrument: No.5

Isolated and X-ray binary pulsars

Isolated pulsars

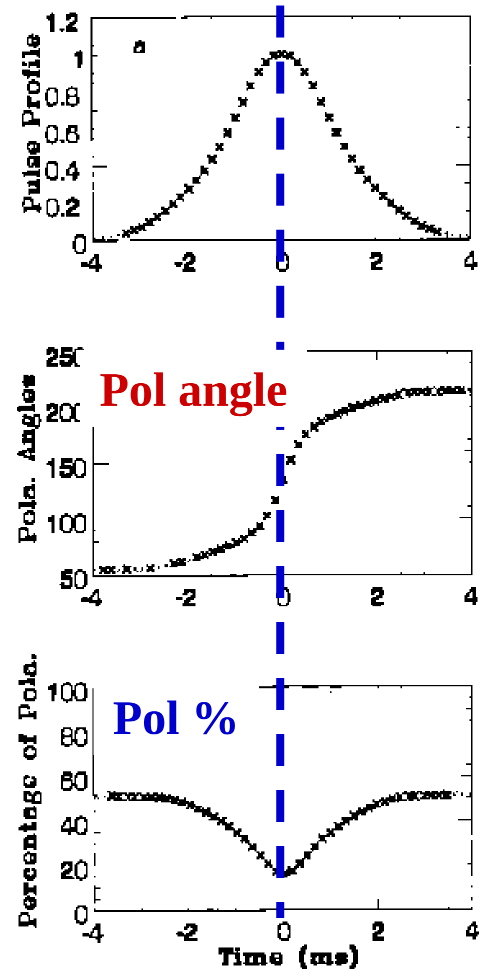


Ginga



Beppo-SAX

Analysis of pol. in optical band by Chen et al.



Crab Polarization Measurements with OSO-8 (Pulsar 1/3)
by a Columbia group (Weisskopf et al.)

THE ASTROPHYSICAL JOURNAL, **225**:221–225, 1978 October 1

SEARCH FOR X-RAY POLARIZATION IN THE CRAB PULSAR

E. H. SILVER, M. C. WEISSKOPF, H. L. KESTENBAUM, K. S. LONG, R. NOVICK, AND R. S. WOLFF
Columbia Astrophysics Laboratory, Columbia University
Received 1978 March 20; accepted 1978 April 10

ABSTRACT

The Crab pulsar was observed at both 2.6 keV and 5.2 keV with the X-ray polarimeters aboard the *OSO 8* satellite. A polarization analysis was performed for various portions of the pulsar light curve, and the polarization contributed by the Crab Nebula was removed. Although there is marginal evidence that the X-ray and optical polarization position angles are similar, no evidence for polarization was obtained at the 3 σ confidence level. Upper limits for the polarization of the pulsar are given in this paper.

Subject headings: polarization — pulsars — X-rays: sources

Crab Polarization Measurements with OSO-8 (Pulsar 2/3)

by a Columbia group (Weisskopf et al.)

TABLE 1

POLARIZATION OF THE PRIMARY PULSE AND INTERPULSE AT 2.6 keV

Parameter	Total Pulse	Central Pulse	Leading Edge	Trailing Edge
A. Primary Pulse				
1. X-ray polarization:†				
Pulse phase bins.........	8–11	9–10	8–9	10–11
R (counts $s^{-1} \times 10^3$).....	96.64 ± 3.15	132.69 ± 4.45	105.69 ± 4.41	87.60 ± 4.41
Q (%)................	$+3.9 \pm 5.0$	$+3.2 \pm 5.1$	-1.6 ± 6.4	$+10.6 \pm 18.4$
U (%)................	-0.3 ± 5.0	-1.6 ± 5.1	-5.3 ± 6.4	-7.1 ± 18.4
Polarization P (%).......	3.9 (+7.4, −3.9)	3.5 (+7.6, −3.5)	5.5 (+9.4, −5.5)	12.7 (+27.3, −12.7)
Position angle ϕ (deg)....	177.6 (+2.4, −177.6)	166.7 (+13.3, −166.7)	53.6 (+126.4, −53.6)	125.4 (+54.6, −125.4)
Π....................	0.73	0.78	0.69	0.79
P^* (%)...............	18.9	19.0	24.8	36.0
2. Optical polarization:‡				
Polarization P (%).......	9.0	7.7	13.8	1.27
Position angle ϕ (deg)....	96.12	103.1	95.0	118.10
B. Interpulse				
1. X-ray polarization:†				
Pulse phase bins.........	25–29	26–28	25–26	28–29
R (counts $s^{-1} \times 10^3$).....	65.94 ± 2.95	77.63 ± 3.78	61.89 ± 4.50	57.36 ± 4.38
Q (%)................	-11.1 ± 6.8	-11.8 ± 7.4	-16.0 ± 11.1	-8.1 ± 11.6
U (%)................	$+3.2 \pm 6.8$	-8.1 ± 7.4	-8.4 ± 11.1	$+25.1 \pm 11.6$
Polarization P (%).......	11.5 ± 9.1	14.3 ± 11.0	18.1 ± 15.3	26.4 ± 17.3
Position angle ϕ (deg)....	81.9 ± 19.2	107.2 ± 18.8	103.8 ± 20.1	54.0 ± 16.6
Π....................	0.23	0.16	0.26	0.08
P^* (%)...............	32.1	36.8	51.6	61.6
2. Optical polarization:‡				
Polarization P (%).......	8.85	9.94	14.32	4.80
Position angle ϕ (deg)....	93.6	94.1	89.86	98.64

† The pulse phase bins are referred to Fig. 1. The remaining parameters for the X-ray polarization measurements are identified in the text.

‡ The optical polarization measurements are from Ferguson *et al.* 1974, analyzed over the same portions of the light curve as were the X-ray data.

Crab Polarization Measurements with OSO-8 (Pulsar 3/3)

by a Columbia group (Weisskopf et al.)

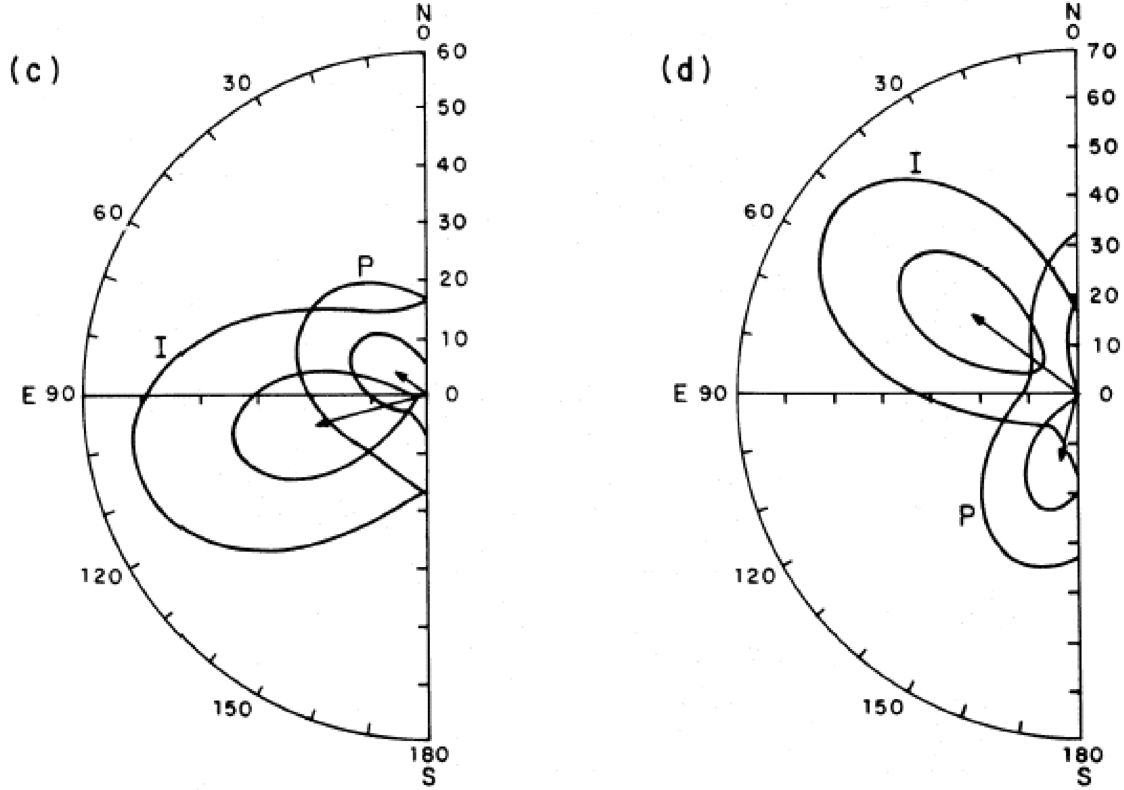
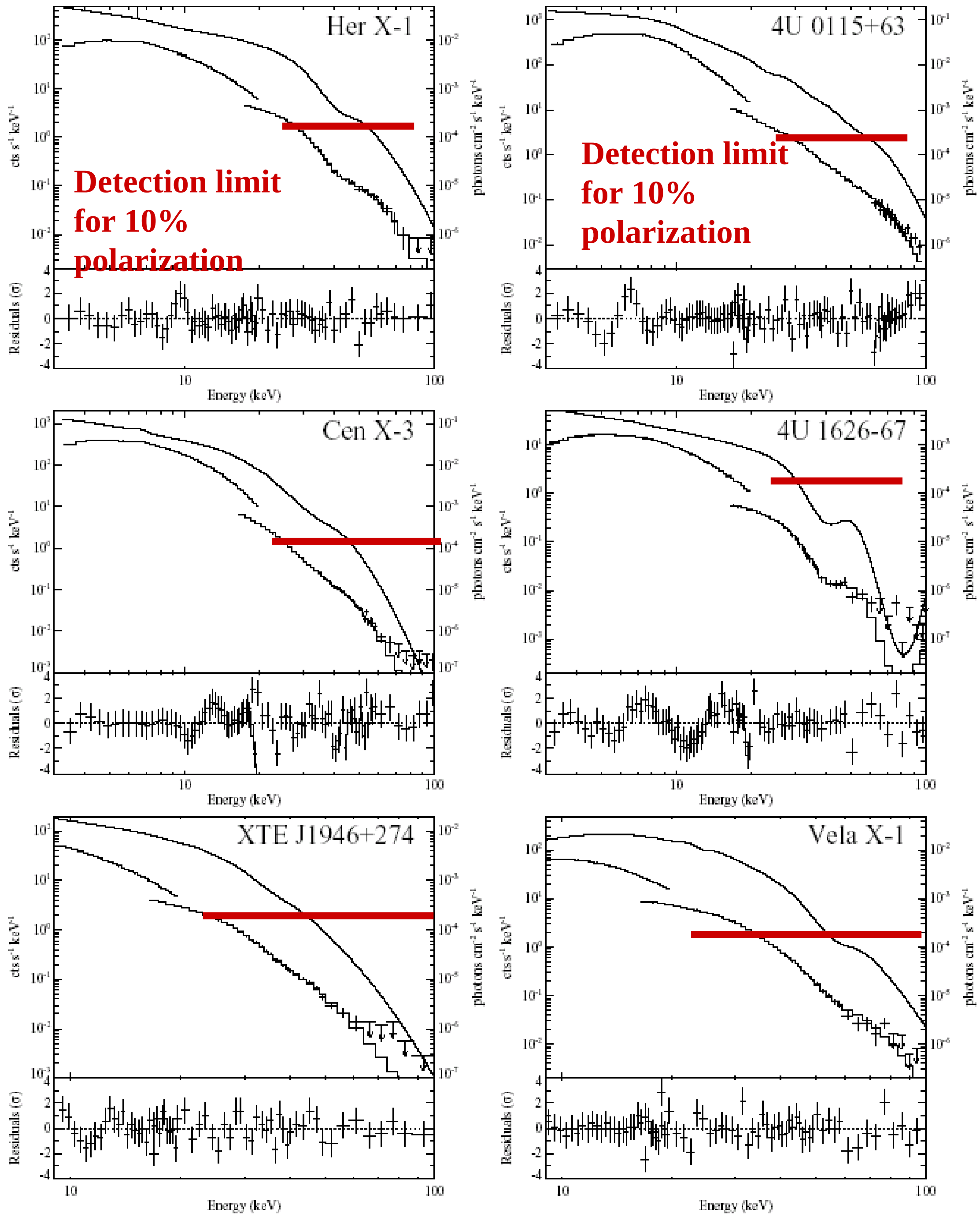


FIG. 2.—The polarization vectors at 2.6 keV for the four pulse phase ranges of the primary (P) and interpulse (I): (*a*) total pulse, (*b*) central pulse, (*c*) leading edge, and (*d*) trailing edge. Surrounding the vectors in order of increasing size are the 67% and 99% confidence contours. The radial scale is the polarization in percent.

Possible Targets of the Instrument: No.6

Isolated and X–ray Binary Pulsars

Binary pulsars with Cyclotron Res. and Scattering Feature (CRSF)

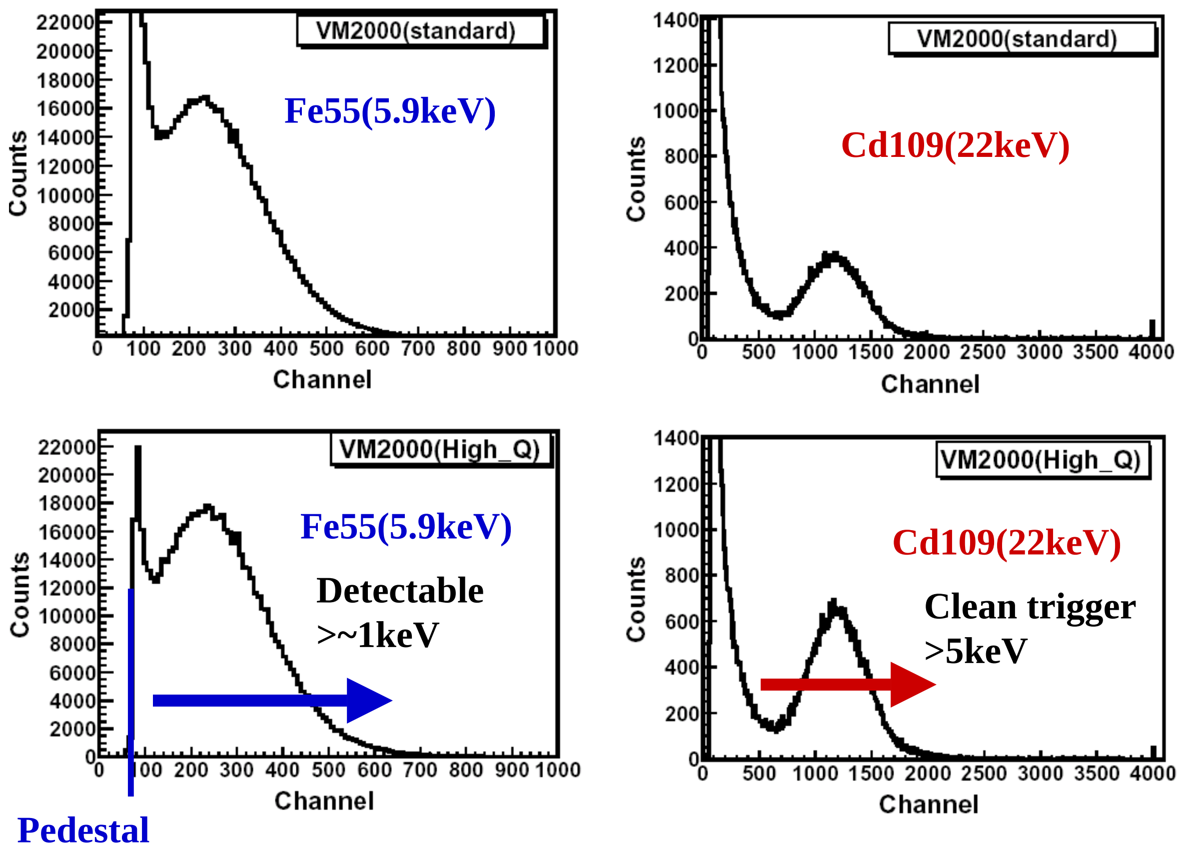


On-Going R/D: No.1

Summary	VM2000(standard)		VM2000 (highquality)	
	Peak	FWHM	Peak	FWHM
Cd109(22keV)	1169ch	11.6keV	1185ch	11.4keV
Fe55(5.9keV)	221ch	8.6keV	230ch	8.1keV

Light yield
of plastic scintillator

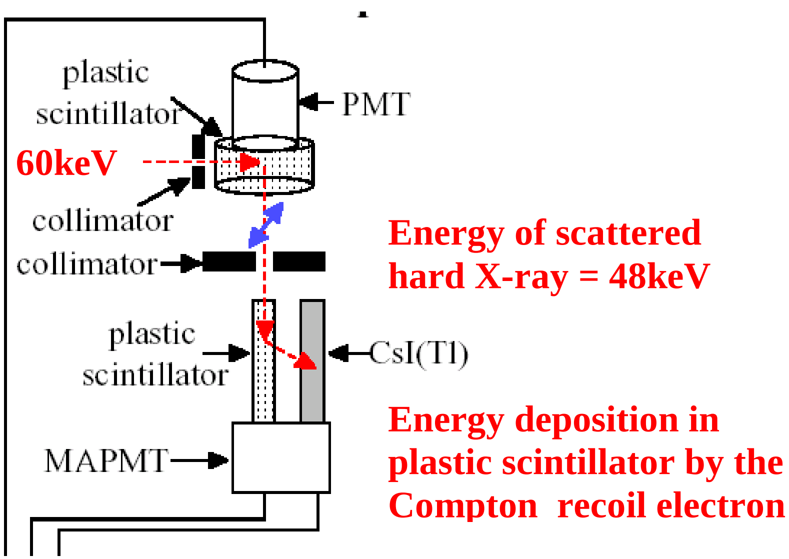
- Minimum triggerable Energy >5keV

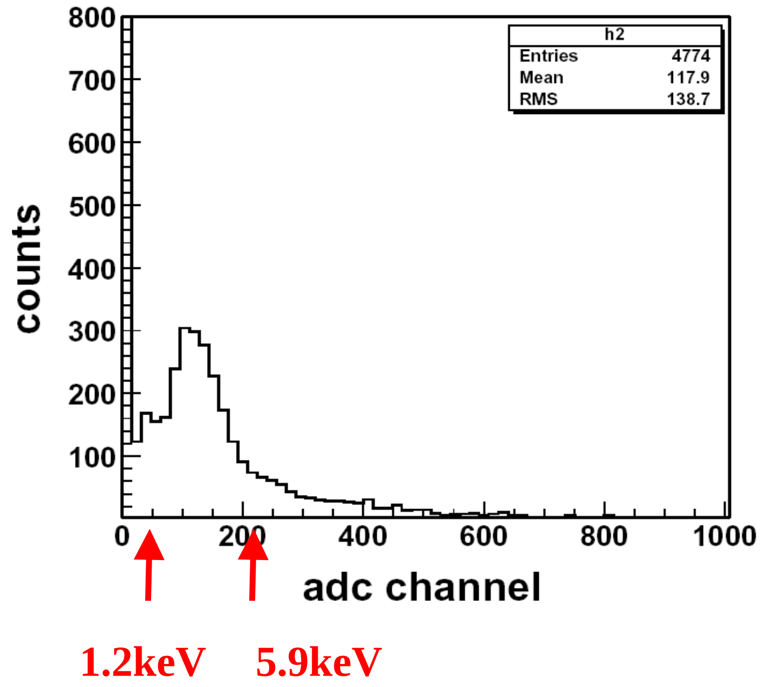


On-Going R/D: No.2

Light yield of plastic scintillator

- **Minimum detectable energy <3keV**

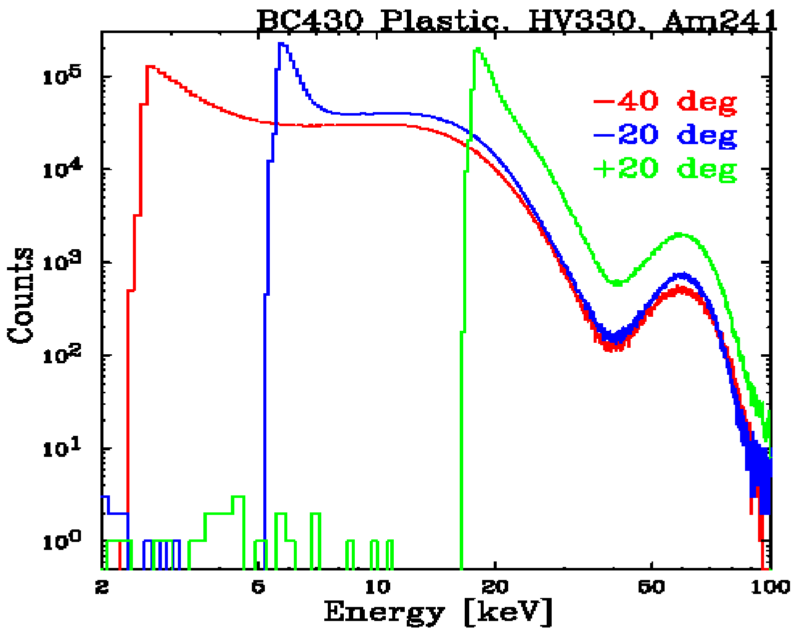


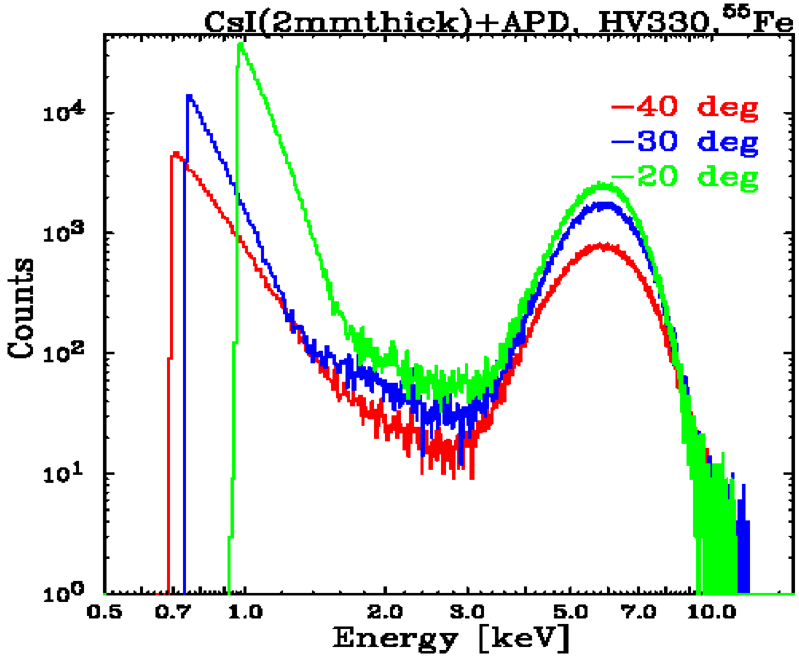


On-Going R/D: No.3

Avalanche photodiode

- **Minimum triggerable energy <10keV**
- **Minimum detectable energy ?**





Summary

- Plastic well-type phoswich Compton polarimeter can detect 10% polarization in 50mCrab sources in a 6hr balloon flight.
- Many interesting targets are in the northern sky.
- Low maintenance: Can fly it within a week of flare alerts.
- Several upgrade possibilities: a satellite mission, several long-duration balloon experiments.

Crab Pulsar	(5h34m32s, +22d0m52s)	**NGC4151**	(12h10m33s, +39d24m20s)
GS2023+338	(20h24m44, +33d52m2s)	**Her X-1**	(16h57m50s, +35d20m33s)
GS2000+25	(20h2m49s, +25d14m11s)	Cen X-3	(11h21m15s, -60d37m24s)
GS1124-683	(11h26m45s, -68d24m31s)	Vela X-1	(9h2m6.9s, -40d33m17s)
A0620-00	(6h22m45s, -0d20m44s)	**4U0115+63**	(1h18m31.9s, +63d44m24s)
Cygnus X-1	(19h58m22s, +35d12m06s)	4U1626-67	(16h32m17s, -67d27m43s)
Mrk501	(16h53m52s, +39d45m37s)	**XTEJ1946+274**	(19h45m34s,+27d23m0s)
GRS1915+105	(19h15m12s, +10d56m44s)		
GX339-4	(17h02m50s, -48d47m23s)		
NGC4945	(13h5m26s, -49d28m15s)		