Using Multilayer Optics to Measure X-ray Polarization

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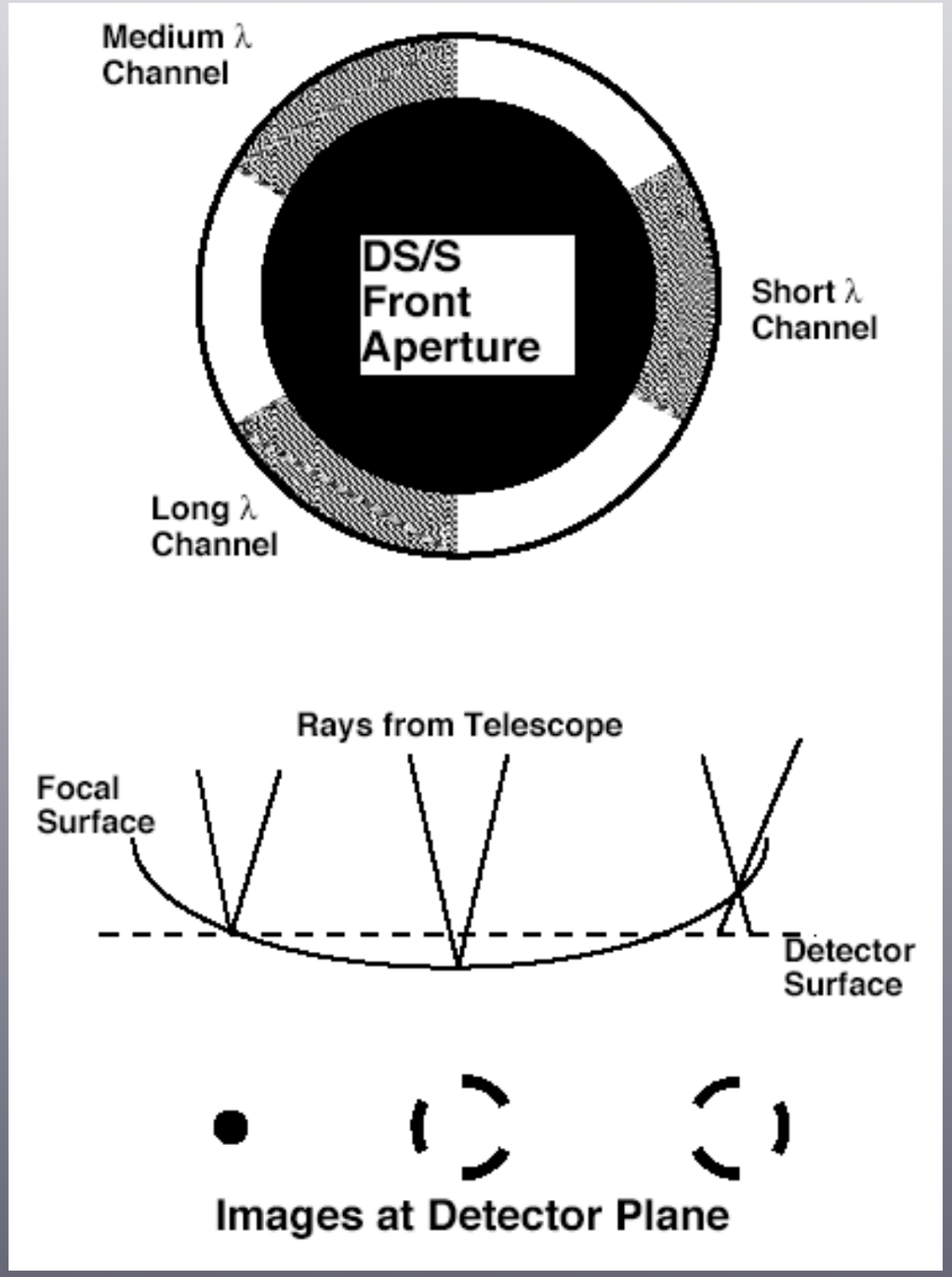
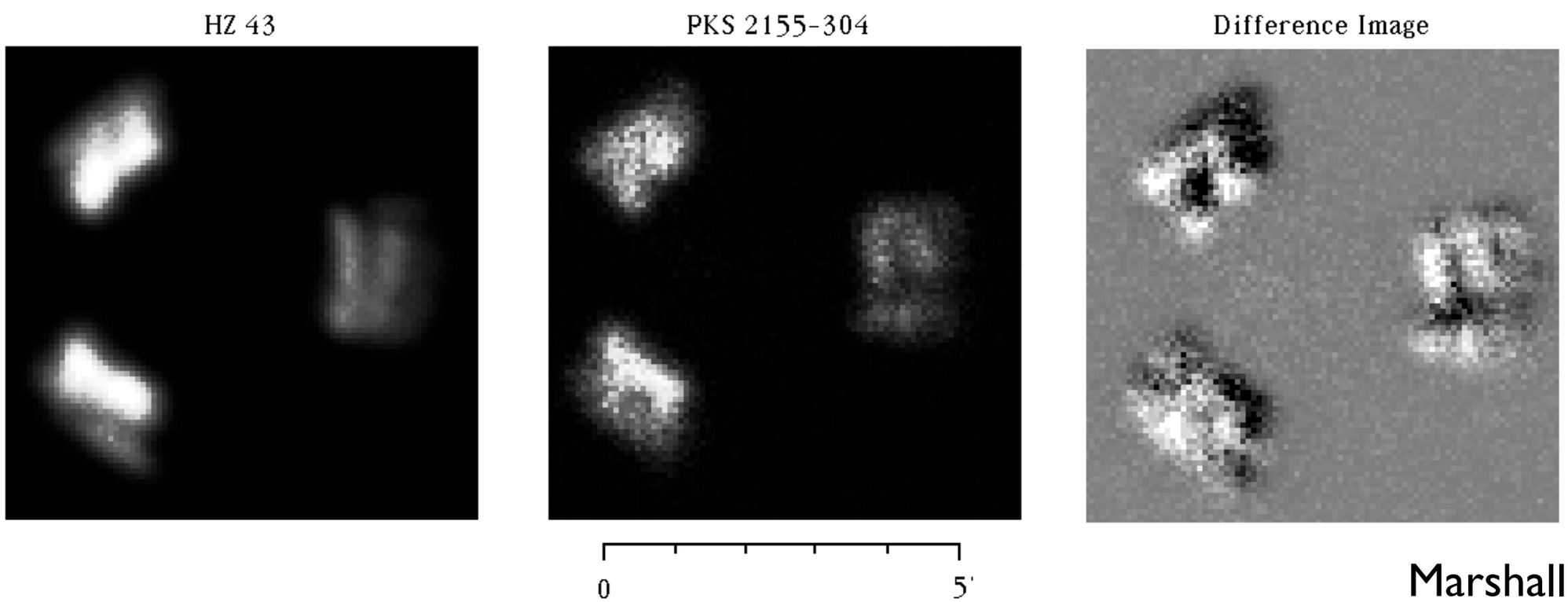
Background: an Attempt to Measure EUV Polarization - 1

- Used Extreme Ultraviolet Explorer (EUVE)
- Deep Survey telescope graze angles were 5-10°, so reflectivity is polarization-sensitive
- DS focal surface is not planar, so off-axis images have shape of aperture
- Predicted modulation factor: 4%
- Observed PKS 2155-304 for 200,000 s, getting 100,000 events



Background: an Attempt to Measure EUV Polarization - 2

- The BL Lac image differs from the WD image
  - Differences are not due to polarized flux
  - Uncalibrated systematic errors dominate
- Motivation to design experiment for soft X-ray polarimetry



Marshall et al. 2001

A Soft X-ray Polarimeter

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- Designed as a polarimeter from outset
  - Mirror angle of incidence centered at 45°
  - Use multilayer coatings to improve reflectivity in X-ray band
  - Chose 250 eV to use common successful multilayer combinations
    - ISM optical depth < 1 for $N_H < 3 \times 10^{20} \mathrm{cm}^{-2}$
    - Maximizes photon flux: $R \propto \delta E n_E \propto f E^{-\Gamma+1}$
  - 3rd generation: image portions of a 3 mirrors using 3 detectors
- Scientific goals
  - Measure AGN polarizations to ± 1% — drives bandpass, area
  - Determine PSR polarization variation with pulse phase — drives timing
  - Observe 50-200 targets in 1-3 yr — drives area
- Proposed as University Explorer (UNEX)
  - Cost cap was $13M, including launch
  - Proposed (then) free Shuttle launch with Spartan carrier
  - Awarded technology development funding

Multilayer Physics

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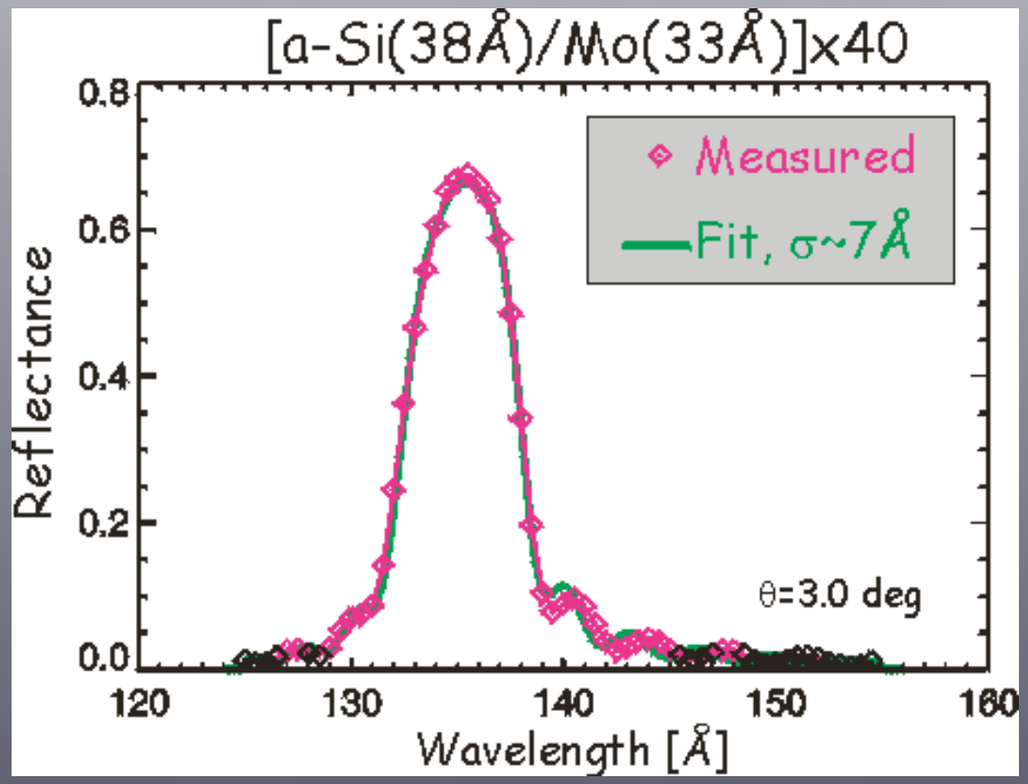
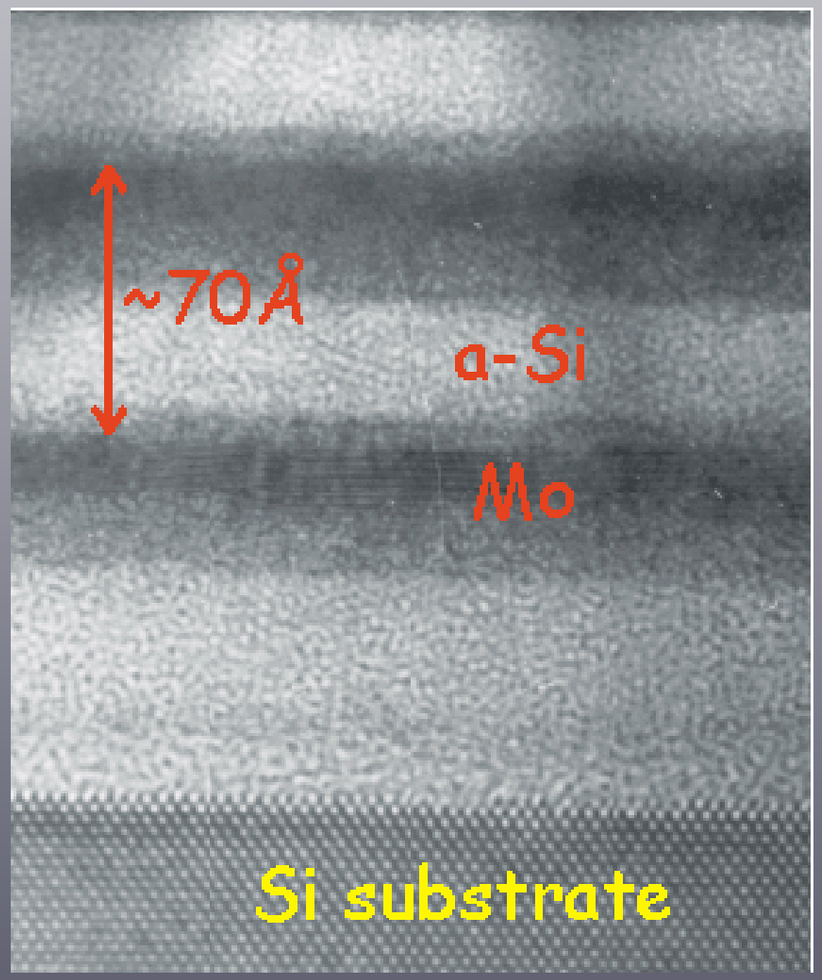
- Multilayer coatings are crude crystals
- Bragg equation gives bandpass peak: $\lambda = 2d\cos\theta$
  - d is multilayer spacing (2 or more layers)
  - θ is angle of incidence
- Interface roughness (2-5 Å) is important
  - Reflectivities are well modelled
  - Feasible peak energy limited to < 1 keV

Figures from Dave Windt's website





Multilayer Measurements

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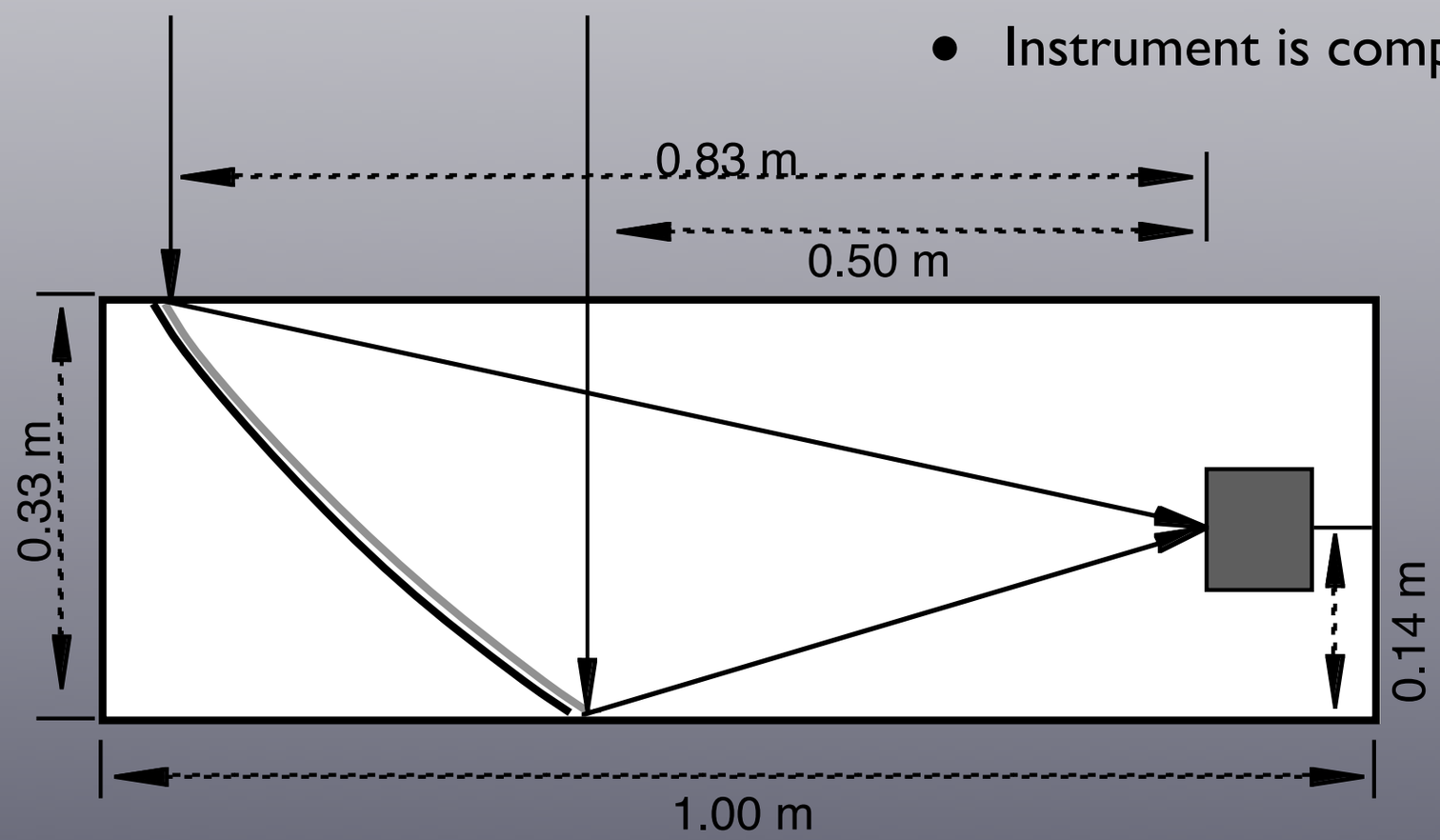
- Excellent multilayers have been deposited
- Models of reflectivities match observations

From CXRO web site, Windt et al.

Material	d (Å)	N	Angle	E	R	dE	Ref.
Ni/C	48	20	45°	180 eV	18%	9 eV	Yamamoto
Mo/B4C	49	100	45°	185 eV	23%	2 eV	Yamamoto
Ru/B4C	49	100	43°	185 eV	19%	2 eV	Yamamoto
Ni/C	31.6	75	45°	277 eV	19%	4 eV	Dietsch
Co/C	30	41	47°	282 eV	12%	7 eV	Grimmer
Ni/Ti	20	75	42°	451 eV	5.9%	9 eV	Grimmer
Ni/V	17	150	44°	510 eV	6.8%	3 eV	Grimmer
Cr/Sc	16	300	2.5°	390 eV	6.9%	1.2 eV	Windt
W/B4C	18.	300	2.5°	690 eV	0.25%	0.3 eV	Windt

Optics Layout — 1

- Mirrors are paraboloidal sectors
  - One bounce system improves reflectivity
- 45° mirror reflection angles
  - Maximizes modulation factor
  - Instrument is compact



Detectors are simple, need only 0.1 mm spatial and no spectral resolution

Optics Layout — 2

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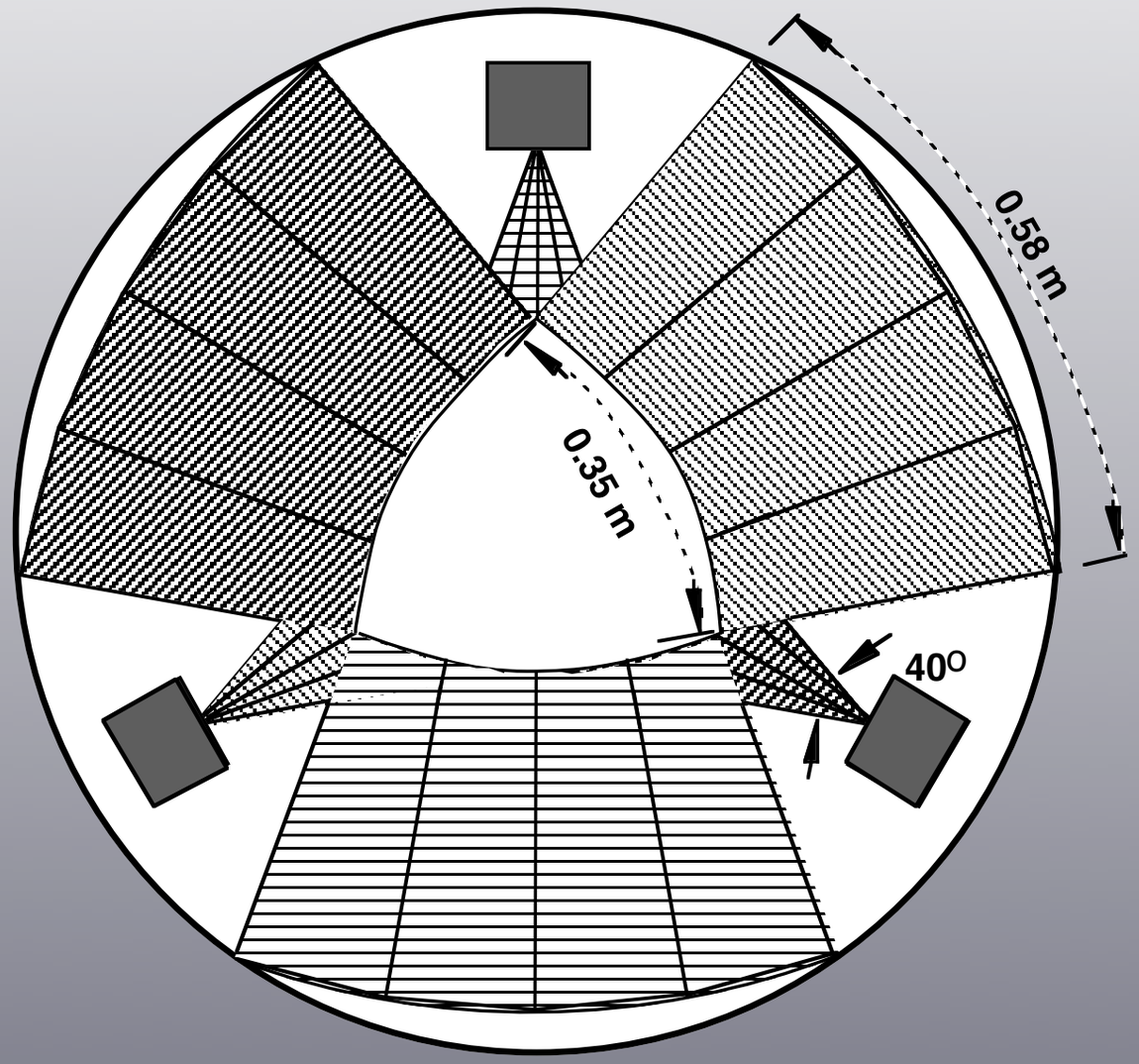
- Mirror assemblies divided into 4 x 10° segments
  - Each assembly has a dedicated detector
  - Mirror/detector combinations are optically identical, F = 0.33 m
- Mirror segments are imaged independently
  - Polarization modulation improves from 70% to 90%
  - Robust to pointing direction
  - Internal background is low, comparable to diffuse X-ray background



Detailed Multilayer Design

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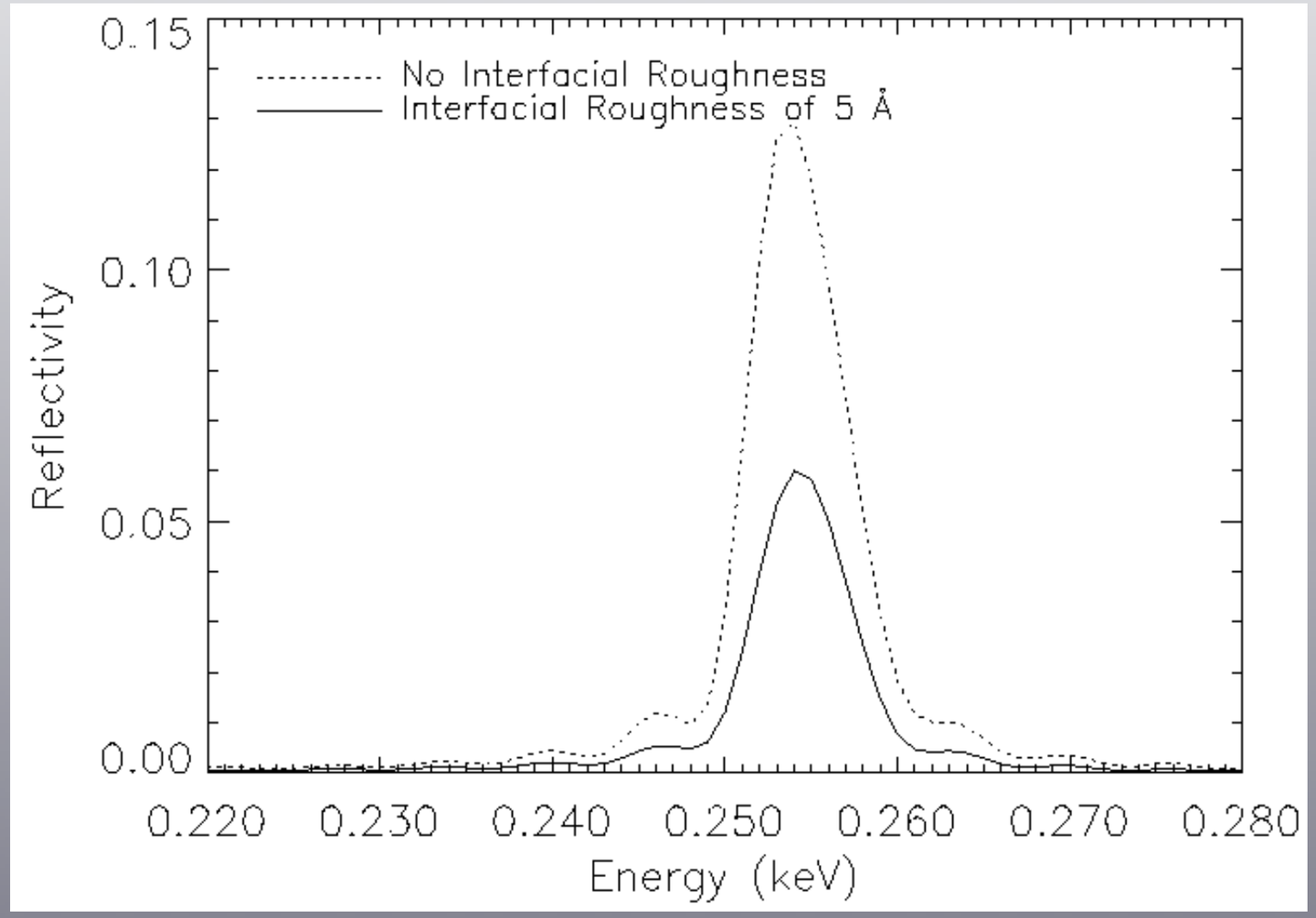
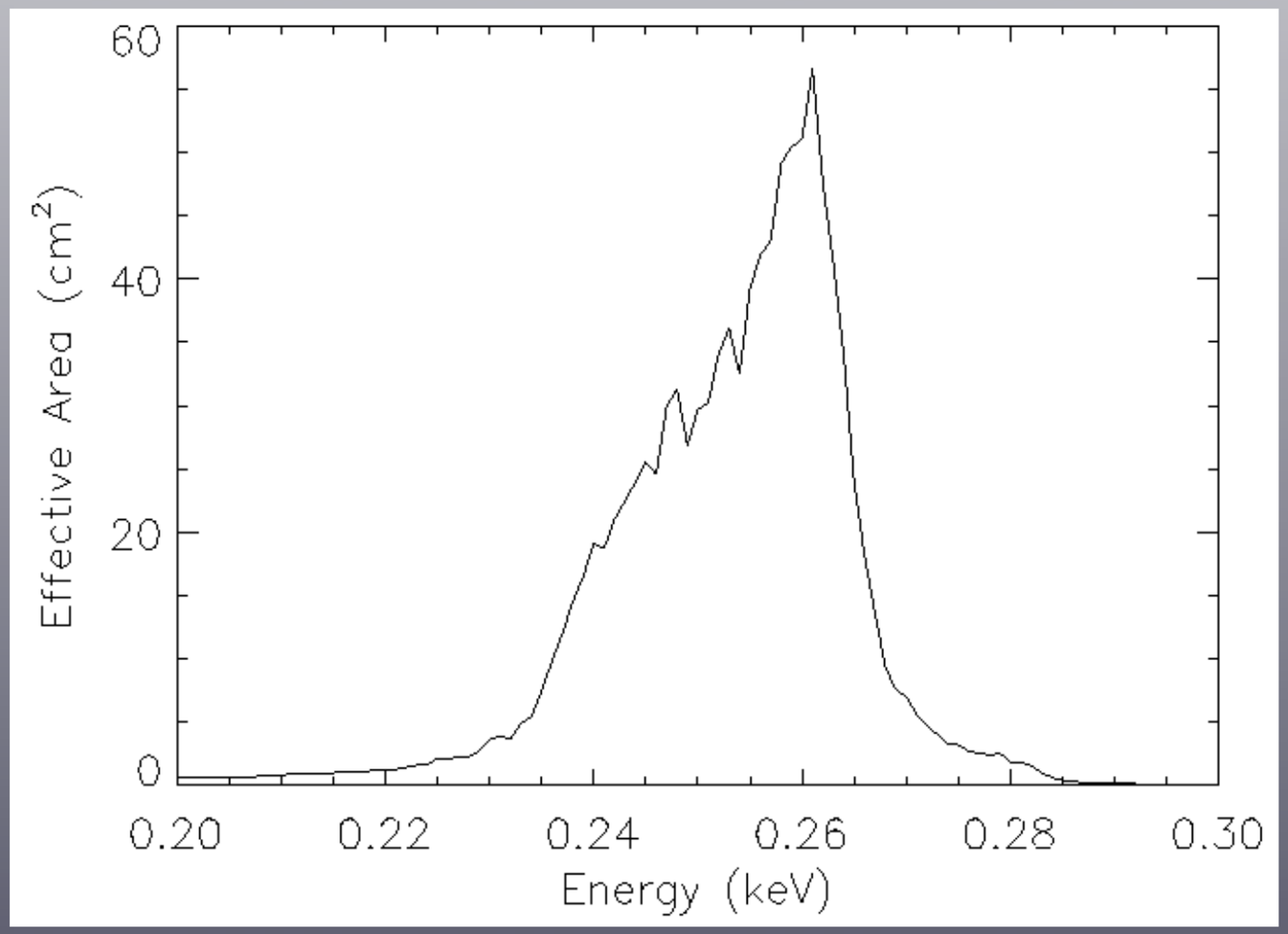
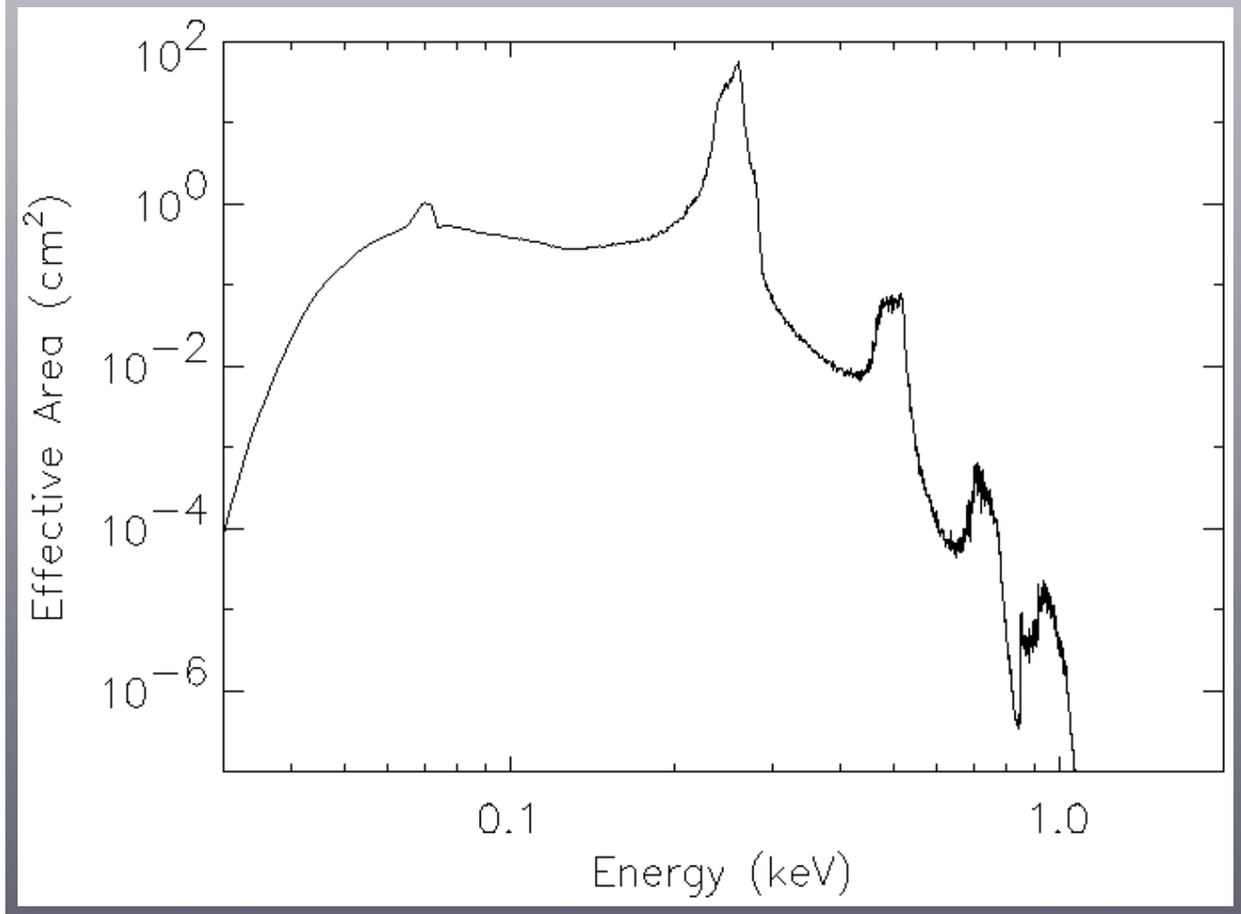


- Use C/Ni Multilayer
  - Spacing (d) is 30-40 Å
  - dC/d = 0.6
  - Modulation factor ≠ f(E)
  - Interfaces are stable
  - C/W and C/Co are also OK
- Include Interface Roughness of 5 Å
  - ML coatings from SAO facility are this good
  - Peak reflectivity decreases x2 from no roughness case

System Effective Area

- Final bandpass includes other effects
  - ML spacing changes along mirror surface based on sputterer distance
  - Lexan/Al filter blocks UV and optical light
- High orders are negligible





System Layout

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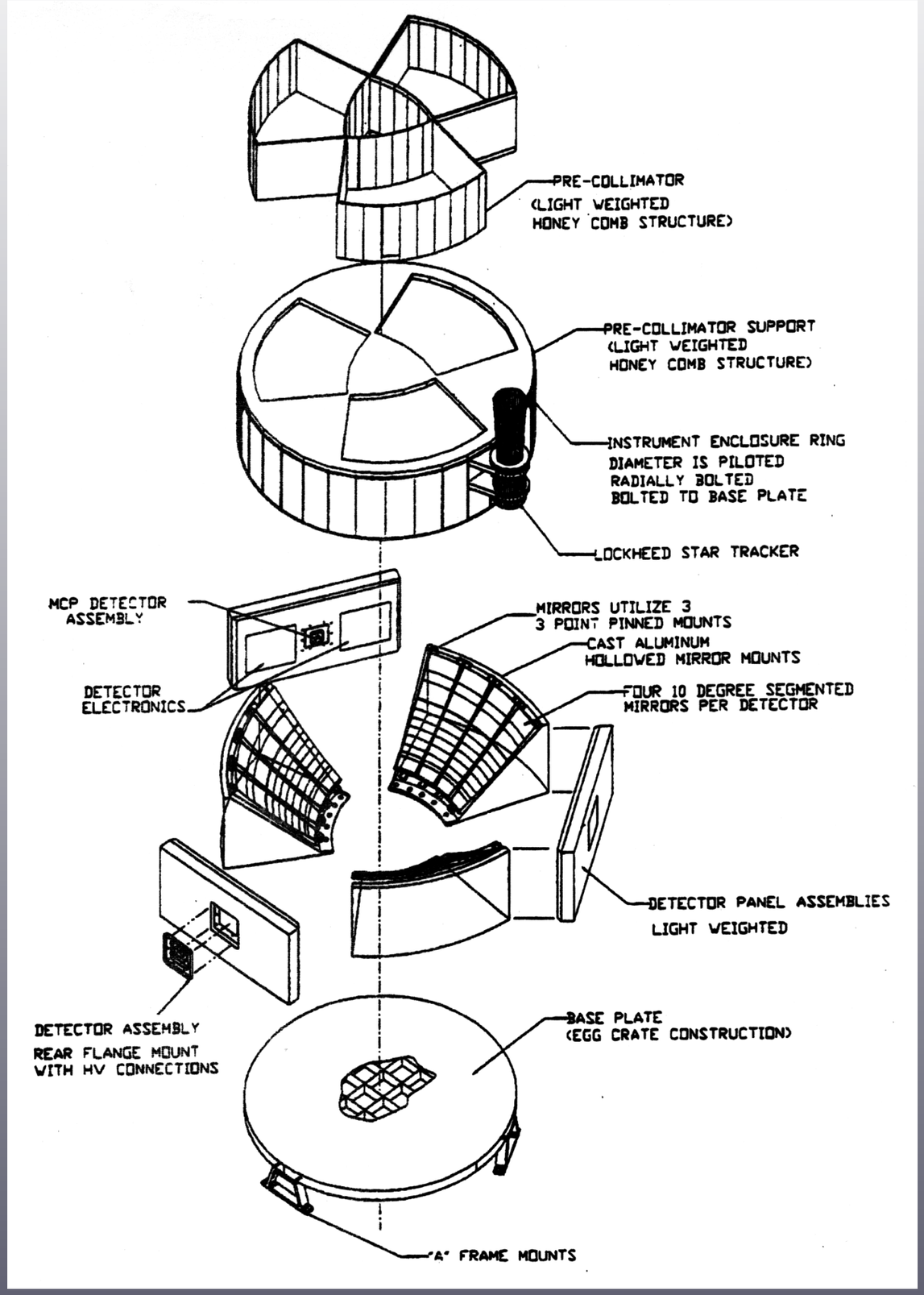
- Interfaces are simple
- Star tracker added for better attitude reconstruction
- Redundant telescopes
- <u>3 Stokes parameters can be measured at once</u>
- Rotate to remove systematic effects



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Sample 90^d Observing Plan

Category	Example	Cnt Rate cnt/s	Exposure (day)	Meas. uncert. (%)	MDP (%)	# visits (in 3 mon)
Pulsar	Her X-1	0.65	0.5	1.21	6.1	4
Pulsar	Vela	0.1	5	0.98	4.9	1
BL Lac	PKS 2155-30	1.3	0.5	0.86	4.3	6
BL Lac	Mkn 421	0.8	0.5	1.09	5.5	6
BL Lac	Mkn 501	0.11	1	2.08	10.4	3
BL Lac	1H1023	0.14	1	1.84	9.2	3
AGN/Quasar	Mk 478	0.25	1.5	1.13	5.6	4
AGN/Quasar	3C 273	0.2	2	1.09	5.5	10
AGN/Quasar	NGC 5548	0.14	3	1.06	5.3	10
AGN/Quasar	1H0419-577	0.17	3	0.97	4.8	3
WD	HZ 43	3.5	0.3	0.67	3.4	3
WD	WD 1502	0.9	0.7	0.87	4.3	3
WD	Sirius	0.63	1	0.87	4.3	3

Science Goals (abridged)

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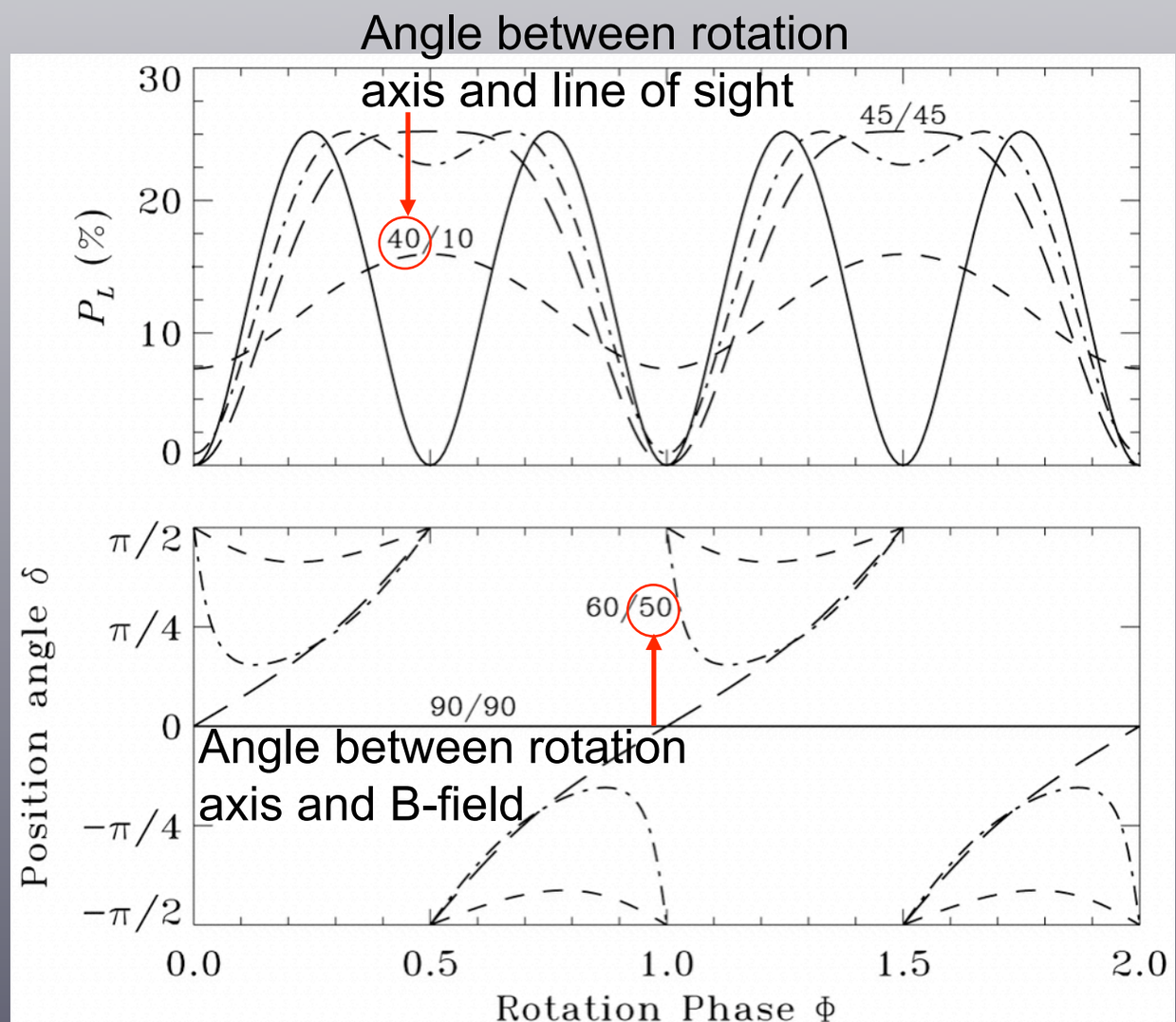
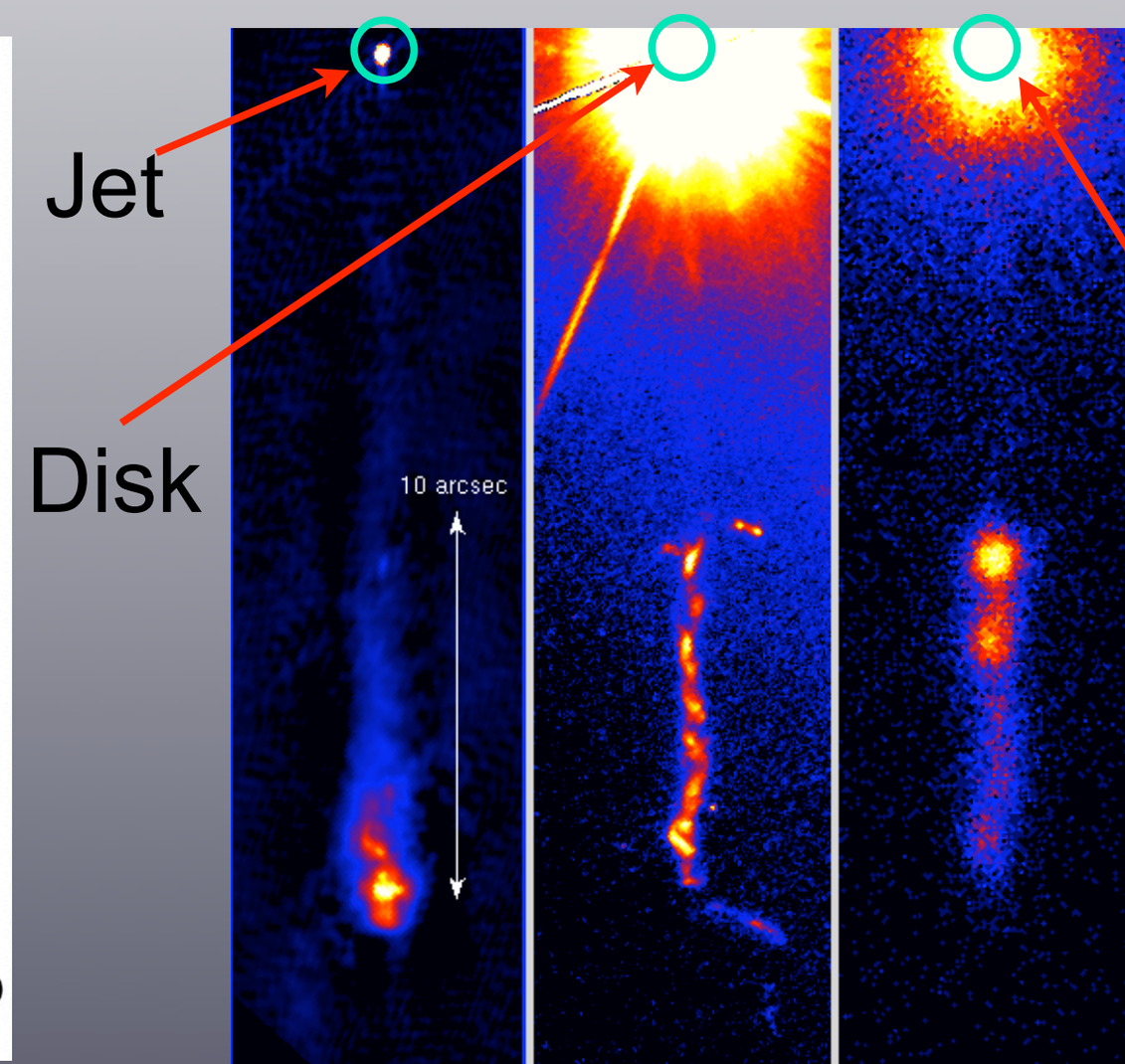
- Quasars: discriminate between jets and disks in quasar core
- Pulsars: determine pulsar B-field geometry, model NS radius with better atmospheres



(Pavlov & Zavlin 2000)



3C 273 (Marshall et al 2001)

X-rays from Radio Jets

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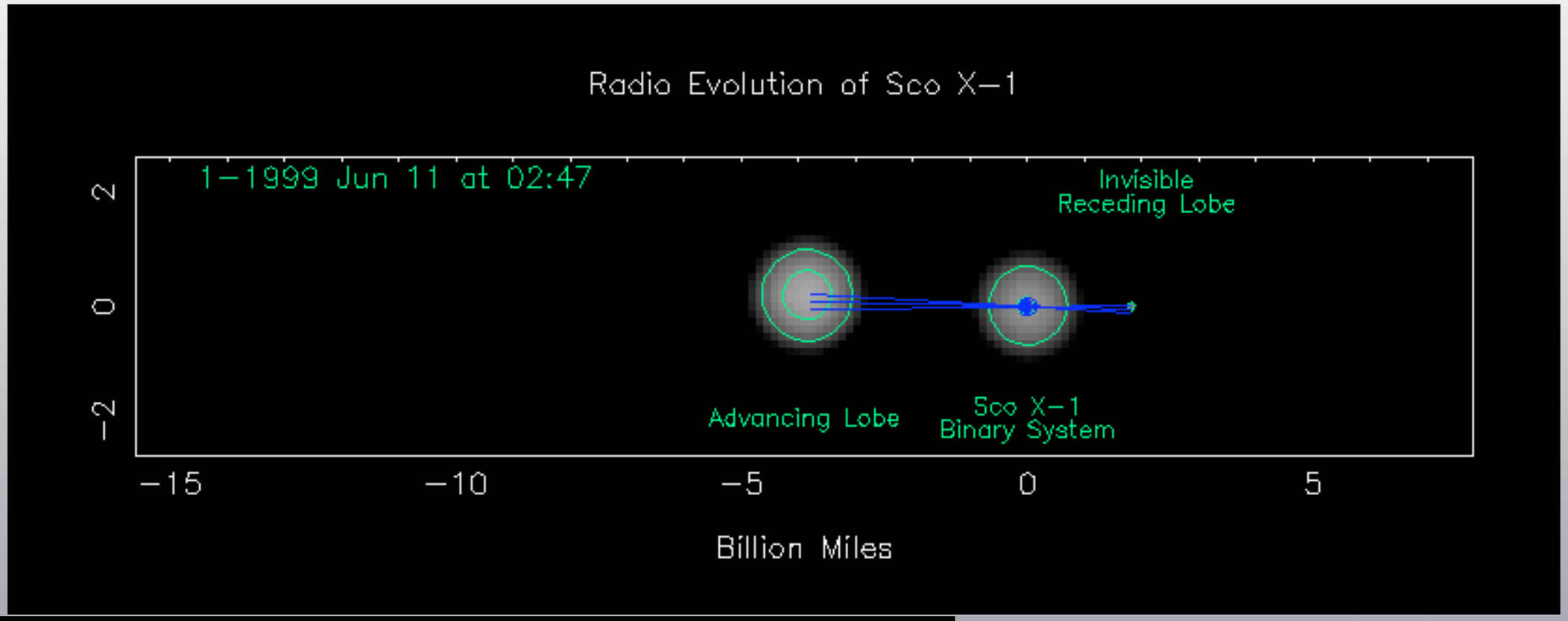
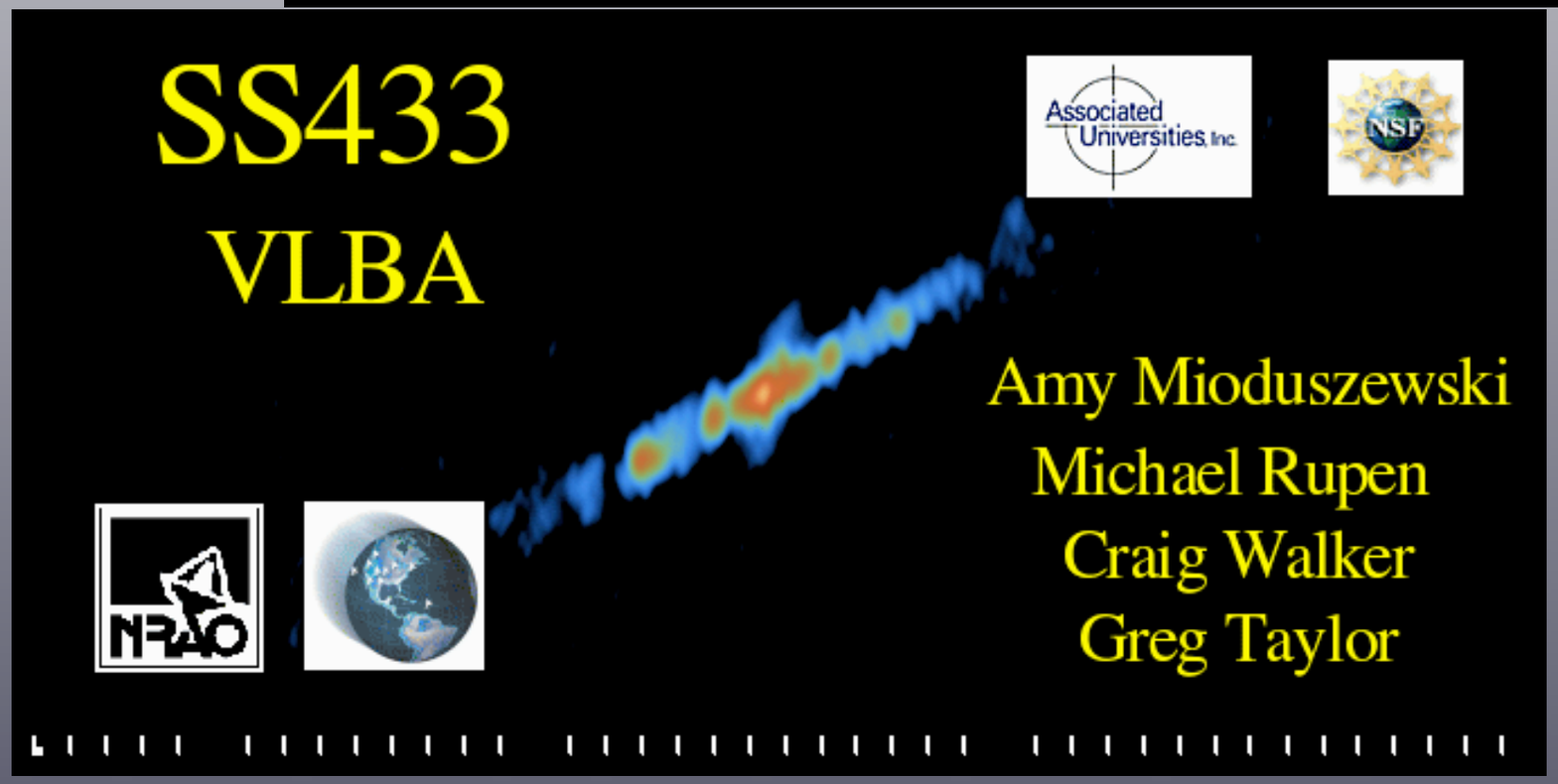
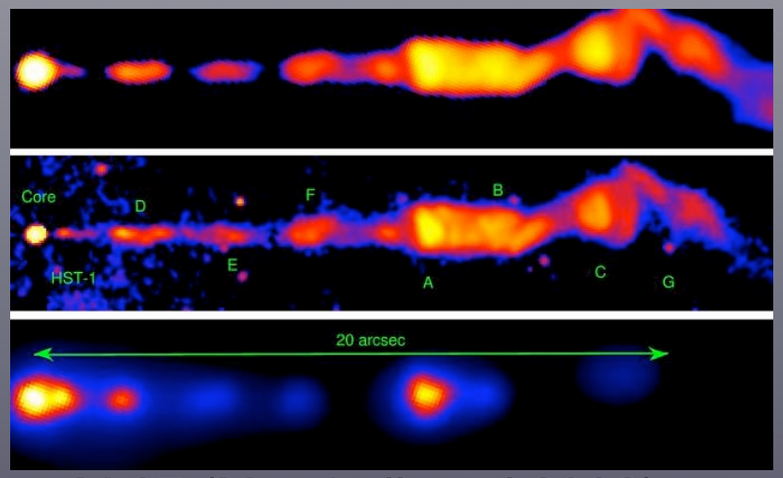
NRAO web site





- VLBA tracks jets



M 87 (Marshall et al 2002)

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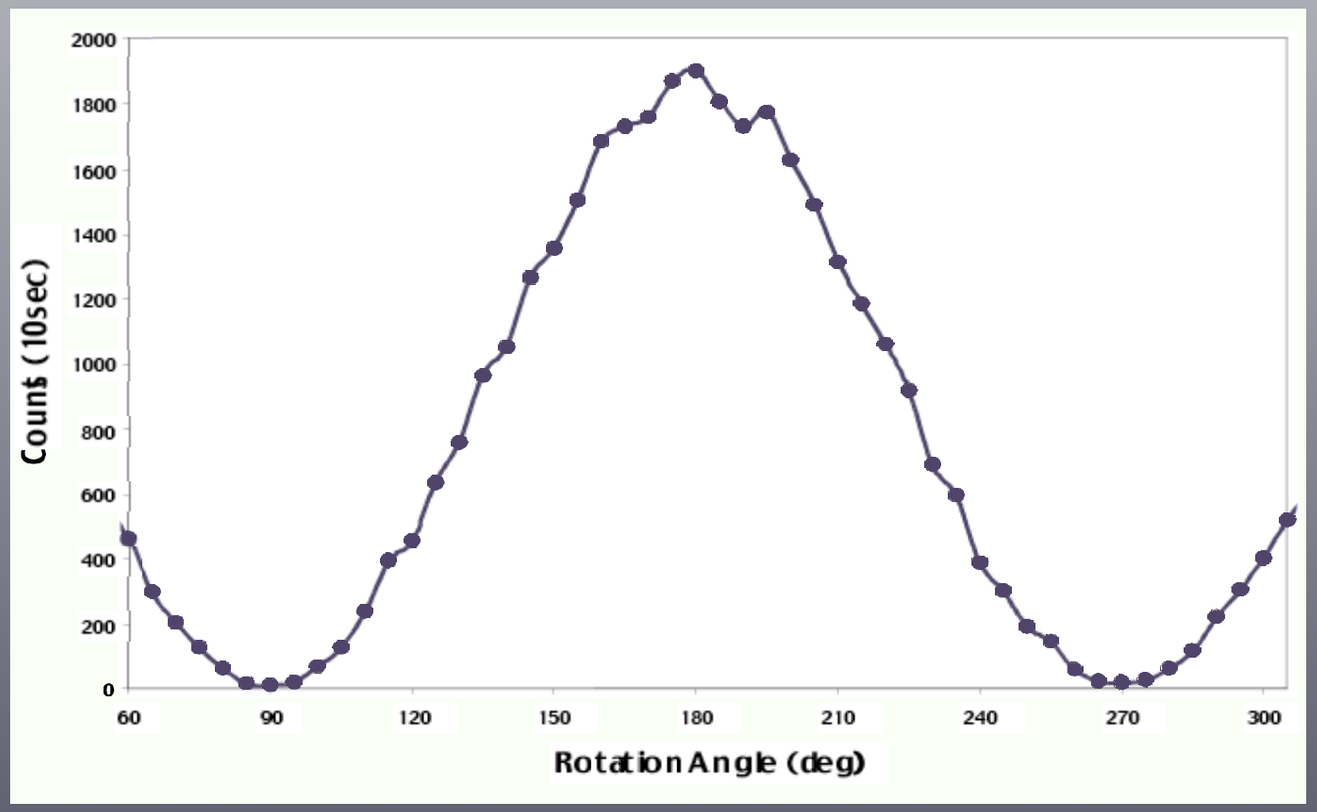
Development Status

- Polarization source built at SAO
  - Output is nearly 100% polarized
  - PLEXAS concept is validated in principle
- UNEX program is gone
  - Add as Mission of Opportunity?
  - Attach to Space Station?



Emily Laubacher (SAO summer intern) works on the polarization source.

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Summary

- A Polarimeter for Low Energy Astrophysical Sources (PLEXAS) is feasible
  - Simple design, low cost and weight
  - Technology is robust and proven to work
- Science potential is wide-ranging
  - Test models of BL Lac jets
  - Test origin of X-rays from quasar cores
    - Discover pc-scale jets in quasar cores
    - Test for rotation of polarization around quasar black holes
  - Measure propagation of light in high B and high g
    - Improve models of neutron stars atmospheres
    - Radius estimates and equation of state depends on atmosphere models
- Looking for (NASA?) development program — good match for 2-20 keV polarimeters