Schedule for M4 Meeting (October 21-22, 1999)

Day 1, October 21, 1999

Note: The sessions from 10:20 through 13:40 on 10/21 will be open to the CfA Community.

Time	Duration	Moderator or Speaker	Topic	Comments
8:50	0:25	Clemens	SMEX Program: Opportunities, Constraints	Including "live" input from J. Howard, Ball Representative
9:15	0:25	Jones	M4/97 - Primary Science Mission, Instrument, S/C, Orbit/Operations	1997 M4 proposal available at web site
9:40	0:25	Laureijs, Schulz	Satellite Polarimetry:ISO - Lessons learned, Enabled Science	Discussion of satellite & data processing issues, science after break
10:05	0:15		Coffee Break	
10:20	0:15	Goodman	Science Intro & Quick Summary of Polarimetric "Discoveries" Since '97	
10:35	0:20	Klaas	ISO PHT Polarimetry	Science results from ISO Polarimetry
10:55	0:20	Greaves	SCUBA Polarization Results	Impact of current & future sub-mm polarimetry on M4
11:15	0:15	Dowell	Wavelength Dependence of Thermal Emission Polarization	Including implications for choice of M4 wavelength(s)
11:30	0:15	Myers	Interferometer Polarization Results & Plans	Impact of current & future sub-mm interferometer polarimetry on M4
11:45	0:20	Heiles	Constraints on the Milky Way B-field from Background Starlight + More	Current & future use of Opt/IR results w/FIR/submm
12:05	0:50		Catered Lunch for Invitees	

12:55	0:25	Lazarian	CMBR Polarization, including MAP's plans	AG talked with D. Spergel & will add information on MAP plans
13:20	0:20	Heyer	Lage CO Surveys, Current & Planned	Discussion of how these surveys will be used with M4 to get "3-D" field
13:40	0:15	Goodman (moderator)	Discussion of Preliminary M4 Science Goals, Identification of Issues to Discuss Further	Notes will be taken & distributed at end of this session.
13:55	0:10		Short Break while Participants Break into Discussion Groups, Leaders & Rooms Assigned	1. Milky Way Survey; 2. Star Forming Regions; 3. Cirrus Survey; 4. Nearby Galaxies
14:05	0:55		Groups deliberate, rank science, estimate needs & observational requirements	One person leads discussion, another takes notes for a summary
15:00	0:05		Short Break while Particpants Reassemble in Main Conference Room	
15:05	0:10	Milky Way Leader	Presentation of Milky Way Survey Goals	Tentative Leader: Goodman
15:15	0:10	Star Formation Leader	Presentation of Star Formation Goals	Tentative Leader: Myers
15:25	0:10	Cirrus Leader	Presentation of Cirrus Survey Goals	Tentative Leader: Heiles
15:35	0:10	Nearby Galaxy Leader	Presentation of Nearby Galaxy Goals	Tentative Leader: Jones
16:00	1:00	Bo Reipurth	CfA Colloquium on pc-scale Outflows, Phillips Auditorium, preceded by Tea	several attendees requested "time off" to attend, no formal M4 sessions then
17:10	0:35	Clemens	M4/99 Primary Science Program described, prioritized. Guest Observer Program discussed, developed.	Discussions of this continue at dinner.

17:45			Day 1 Formal Sessions End	
18:30			Dinner, with wine & discussion, at Local Restaurant	Transportation will be arranged.

Day 2, October 22, 1999

Time	Duration	Moderator or Speaker	Topic	Comments
9:15	0:20	Goodman	Review/Discussion of M4 Mission, v.99, as it Stands After Day 1 & a Good Night's Sleep	
9:35	0:30	Howard/Ellis	Technology I: Ball Instrument & S/C	Including discussion of similar projects in accomplished
10:05	0:25	Young	Technology II: Arizona Ge Detector Arrays	SIRTF technology, current technology, future technology
10:30	0:20		Coffee Break	
10:50	0:30	Clemens	M4 Management Issues, Structure, Plan	Description of steps that need to be accomplished
11:20	0:30	Jones	M4 Schedule Discussion	Goals, Deadlines
11:50	0:30	Clemens (moderator)	Science Team Assignments	"Volunteers" will be drafted for future tasks
12:20	0:10		Pre-Lunch-Talk Break	
12:30	1:10		CfA "Radio Group" Lunch Talk, by M4 Meeting Participant(s)	Lunch provided for participants
13:40	3:00	Clemens/Jones (moderators)	M4 Implementation Discussions	Including: Requirements, Data, Mission Lifetime Orbit, Instrument, Telescope, Light Analysis,S/C, Data Xfer, Operations, Trade Studies
16:40			*Meeting Adjourns*	Informal Dinner to be Arranged

Click here to Return to Main M4 Page.

Last Updated on 10/12/99
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SMEX Program: Opportunities & Constraints

Dan Clemens

Institute for Astrophysical Research (IAR)

Boston University

Outline

- Welcome
- Meeting Goals
- Meeting Structure
- NASA's Small Explorer Program for 2000
- Timeline/Schedule for this Announcement of Opportunity (AO)
- Odd, Ends, & Technomagerialbabble
- Proposal Document Contents & Constraints
- Cost - M4's 900lb gorilla

Meeting Goals

- Highest Priority
  - Identify and describe the best science program which can be accomplished by M4 given SMEX program constraints
  - Identify and describe the most cost effective M4 implementation which will deliver the data required by the science program within SMEX constraints
  - Identify and deputize key individuals who will take responsibility for contributing components of the M4 proposal
  - Identify and describe a management plan for M4, including naming individuals in all key project positions

Meeting Goals II

- Priority
  - Identify trade studies and calculations which must be performed to support the M4 proposal
  - Identify individuals/units who will perform the trade studies and calculations
  - Identify high risk items in the instrument, S/C, operations, data processing/analysis, and management
  - Recommend alternatives or mitigations for high risk items
- Important
  - Build a strong team spirit and have some fun along the way
  - Identify ground-based or airborne studies which would help leverage M4 and vice-versa
  - Recommend potential reviewers to NASA
  - Gain increased understanding of space-based astrophysics mission elements and capabilities.

Meeting Structure

- Two, overlapping meetings:
  - Science meeting - designing the best M4 science
  - Techniques meeting - designing the best M4 satellite
- Science First
  - Describe SMEX program
  - Describe M4/1997 Science, Implementation
  - Recent Science update (ISO, JCMT, etc.)
  - Revisit M4 Science Plan
- Hardware & Operations Second
  - Detectors
  - Dewars, Instrument
  - Spacecraft (S/C)
  - Operations
- Firm Writing Assignments
  - Red Team meets in 4 weeks

NASA's SMEX Program

- Part of the Explorer Program

Class	Cost	Frequency
UNEX	7.5M$	1 / yr
SMEX	75M$	1 / yr
MIDEX	150M$	1 / yr

- Last two SMEX calls for proposals (AOs)
  - 1997: M4
  - 1993: PIREX
- Rapid design, development, launch
- This year's AO specifies two launch dates:
  - prior to July 2003
  - prior to July 2004

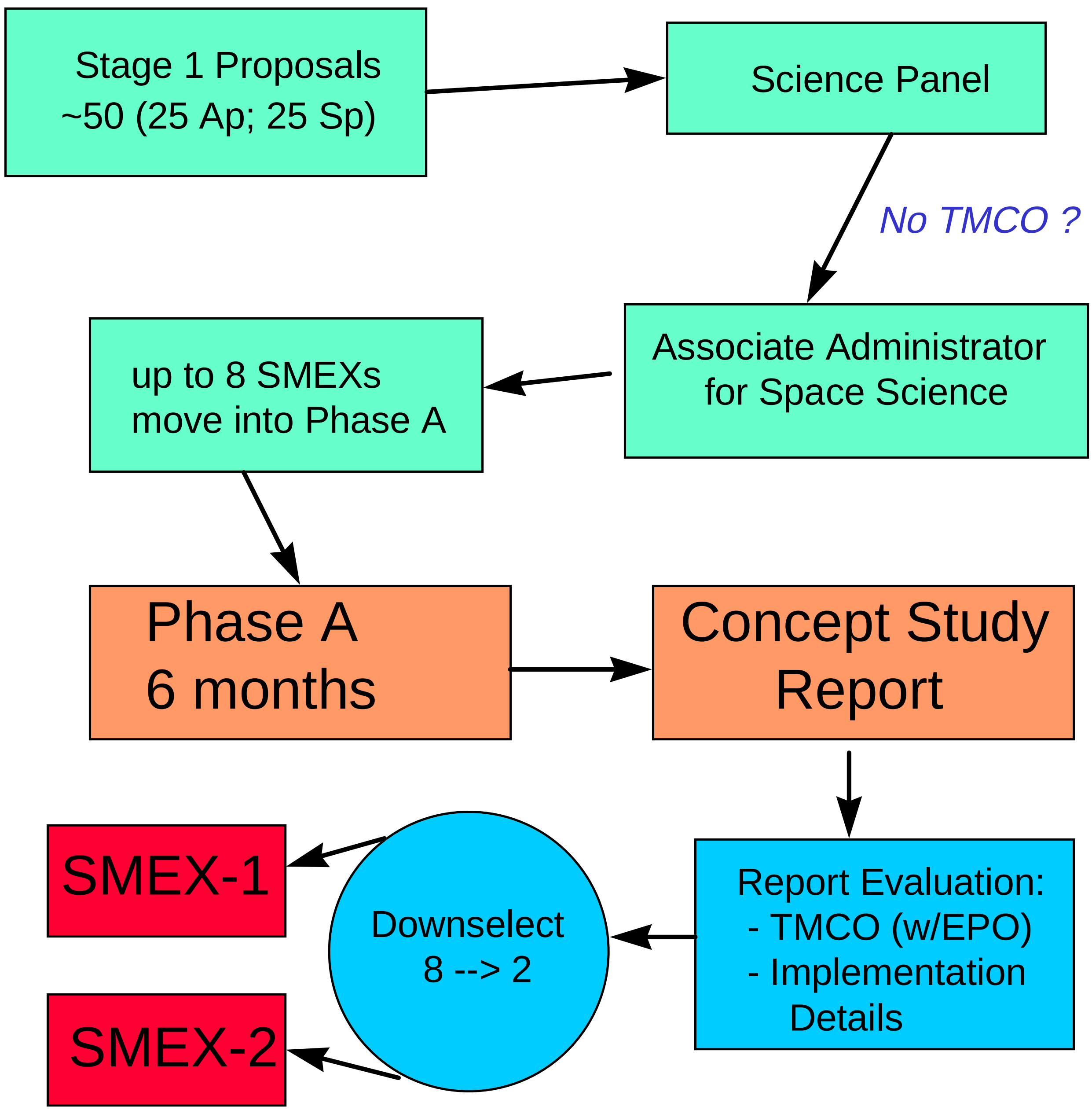
NASA Nomenclature Primer

- Project Phases:

Phase	Name	Notes
A	Concept Study	CSR; 6mo.; 0.45M$
B	Definition/Preliminary Design	PDR
C	Detailed Design	CDR
D	Development to Launch	L+30
E	Mission Operations & Data Analysis	PI retirement

- Launch Vehicles
  - (S)ELV - expendible launch vehicle (e.g. Pegasus)
  - LDB - long duration balloon (9-21 days)
  - Shuttle

SMEX 2000 Selection Process



Milky Way
Magnetic Field
Mapping
Mission

Selection Timetable

AO Release	mid-October
Preproposal Conference	mid-November
LOI due	mid-November
Proposals due	mid-January 00
Phase A selections	April 00
Contracts awarded	May 00
Concept Study Reports due	November 00
Downselection	February 00

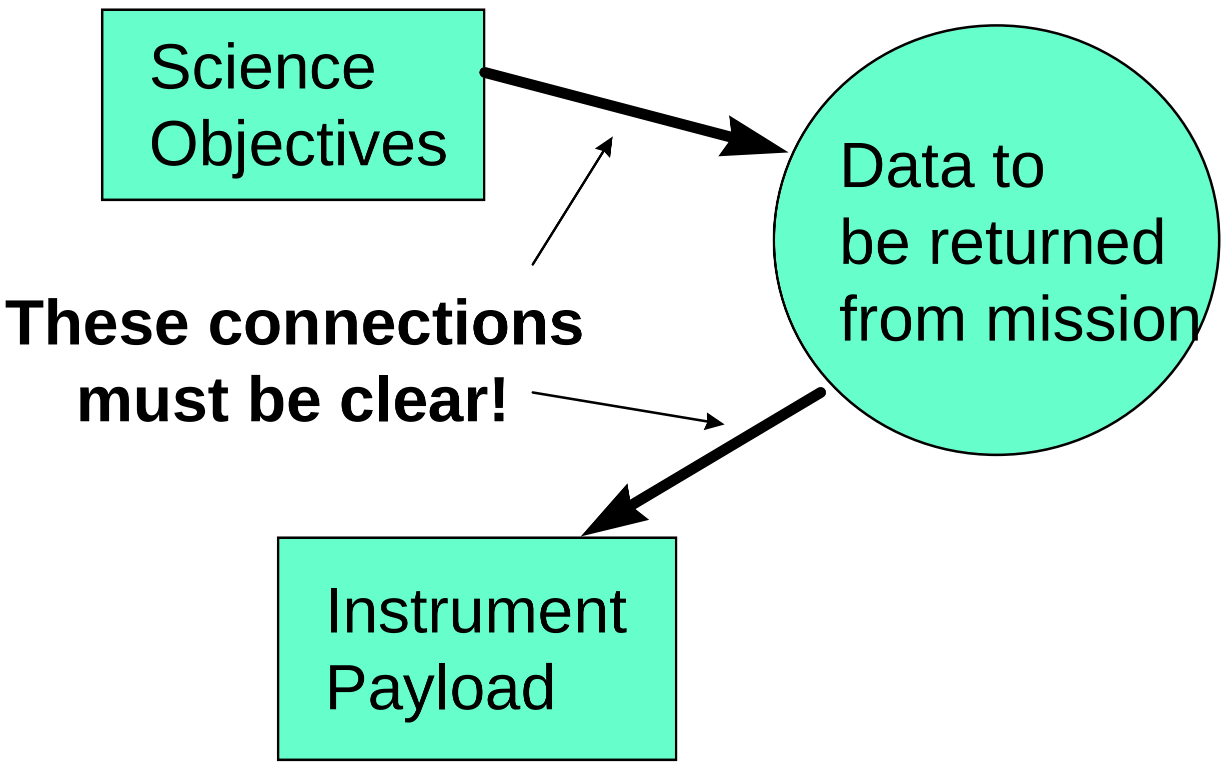
SMEX Goals, Components

- *"Space Science Enterprise Strategic Plan: Origins, Evolution, and Destiny of the Cosmos and Life"* (Nov '97 NASA pub.)
- Modest programmatic scope
  - focussed investigation
  - complement major flight missions
  - prove new science concepts
  - must *require* flight
- Innovative, streamlined, efficient management approaches
- Reduced cost
  - mission lifecycle costing
  - cost limits
  - full cost accounting
  - control processes (business, technical)
  - new technology

PI & Team

- Responsibility for implementing investigation
- Large degree of freedom to accomplish objectives
- Only essential NASA oversight (GSFC provided)
- Responsible for designing in and managing margins, reserves, and resiliency

Science Requirements & Data



- Team must:
  - Perform initial data analysis
  - Deliver data to NASA archive
  - Publish findings
  - Implement EPO program
  - Communicate results to public

Technical Approach Buzzwords

- Technical approach must be consistent with NASA Handbook NHB 7120.5 A *“Management of Major Systems Programs and Projects”*
- Product assurance consistent with ISO 9000 series
- Explorer Project Library
  - Library of on-line manuals, tables, and reports relevant to Explorer Program
  - SMEX Library separate from UNEX and MIDEX Libraries (why? dunno…)
  - http://explorer.larc.nasa.gov/explorer/epl.html

Odds and Ends

- Single PI leads Team
- "Co-Investigators" are paid to work on the project
  - directly by project
  - or, by home institution
    - must include such contributed costs in budget, as per "full cost accounting"
- Each project must have a Project Manager
  - selected by PI/Team (not NASA)
  - oversees technical implementation of mission
- *"Participation by non-US individuals and/or institutions as team members or contributors to Explorer investigations must be endorsed by the institutions and/or governments involved."*
- E&PO plan deferred until Phase A
  - expect to allocate 1-2% of budget (minus launch)
  -

Odds & Ends II

- Phase E (MO&DA) has no time constraint.
- SMEX/2000 cost cap is 75M$ in Y2000 $
  - "in year" $$ are going to be somewhat higher
- Can distribute funds across project phases and elements as best suits investigation
  - Gives more flexibility
  - Puts Phase E (MO&DA) at extreme risk
    - Instrument+S/C eat entire budget w/o controls
- "Total Mission Cost" can exceed "NASA Mission Cost"
  - contributions welcome
  - full cost accounting will add non-NASA costs
  - limit is 2x NASA Cost (e.g., 150M$)

Proposal Elements & Limits

- 30 page limit (with some exclusions)
  - including no more than 2 fold-outs
- TOC - 2 pages
- Science Investigation - 20 pages
  - Science Goals & Objectives
  - Science Implementation
    - Instrument
    - Mission
    - Data Analysis & Archiving
    - Science Team
- Mission Design - 8 pages
  - includes management, schedule, cost
  - also E&PO and SDB statement of compliance
- Appendices
  - Statemenst of Work (SOW)
  - Letters of Endorsement
  - Resumes
  - Acronyms List
  - Reference List

Cost - M4's 900lb gorilla

M4 Budget Overview - 1997 and 1999
(Costs in $1000)

Category	1997			1999		Delta
			Ball ROM			
Science Team (inc. EPO)	$9,254			$9,000		-$254
Instrument	$18,577		*$19,689*	$18,500		-$77
S/C	$11,804		*$13,961*	$11,900		$96
Contingency (as % of Inst+S/C)	$3,529	11.62%		$6,080	20.00%	$2,551
(as % of non-launch total)		8.01%			13.85%	
I&T and Ground Sys.	$4,448			$4,500		$52
Launch (Pegasus)	$19,000			$25,000		$6,000
Total FY97 Dollars	$66,612					
Total FY00 Dollars				$74,980		

M4 1997

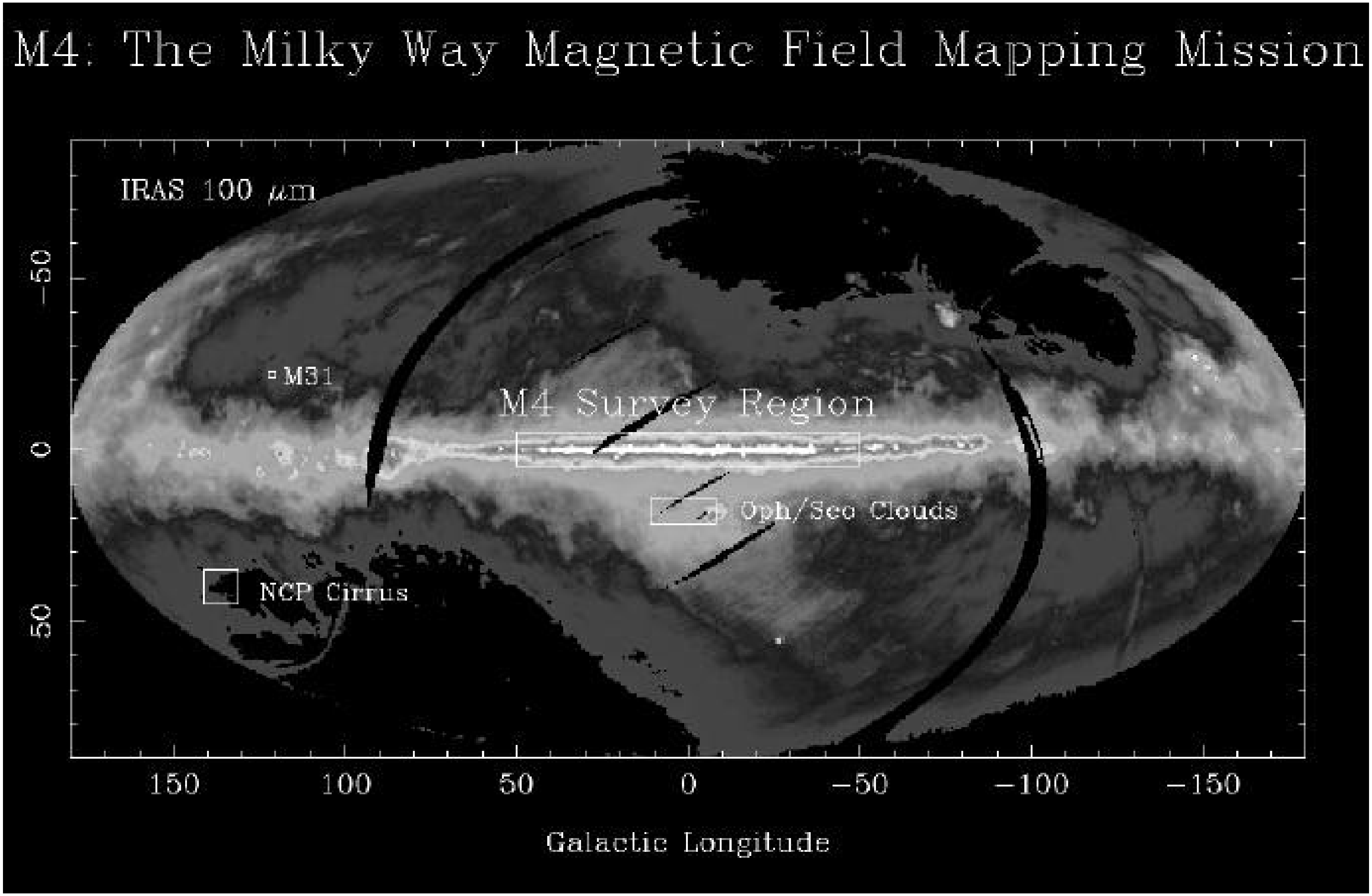
The Proposal

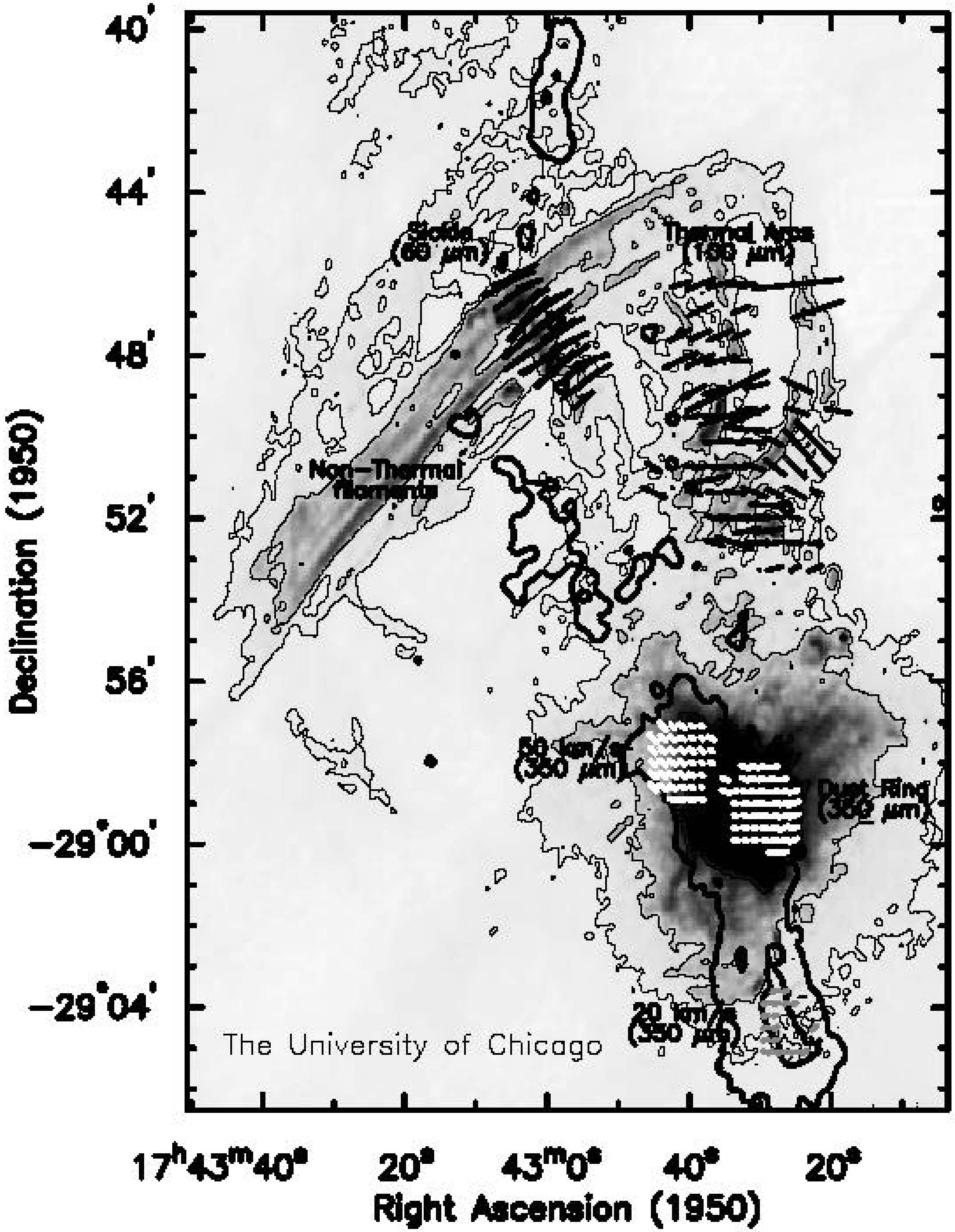
Points to keep in mind:

1. M4 was to be built from scratch as a polarimeter.
2. Science was the primary driver for the project.
3. Science goals and technical capabilities had to agree.

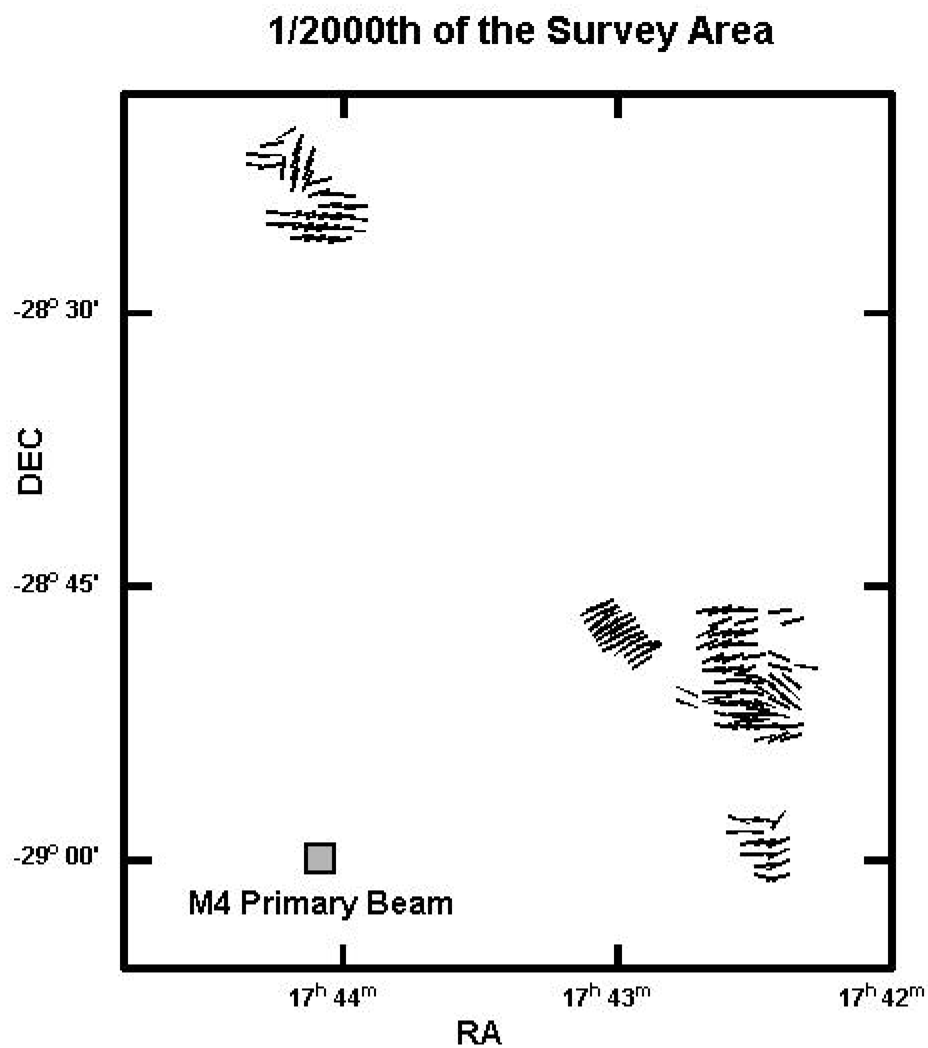
Primary Science Goals

- What is the magnetic field structure in the ISM of the Milky Way?
- What role do magnetic fields play in the star formation process?
- What magnetic field structures exist in the infrared cirrus?
- What is the global magnetic field structure in M31?

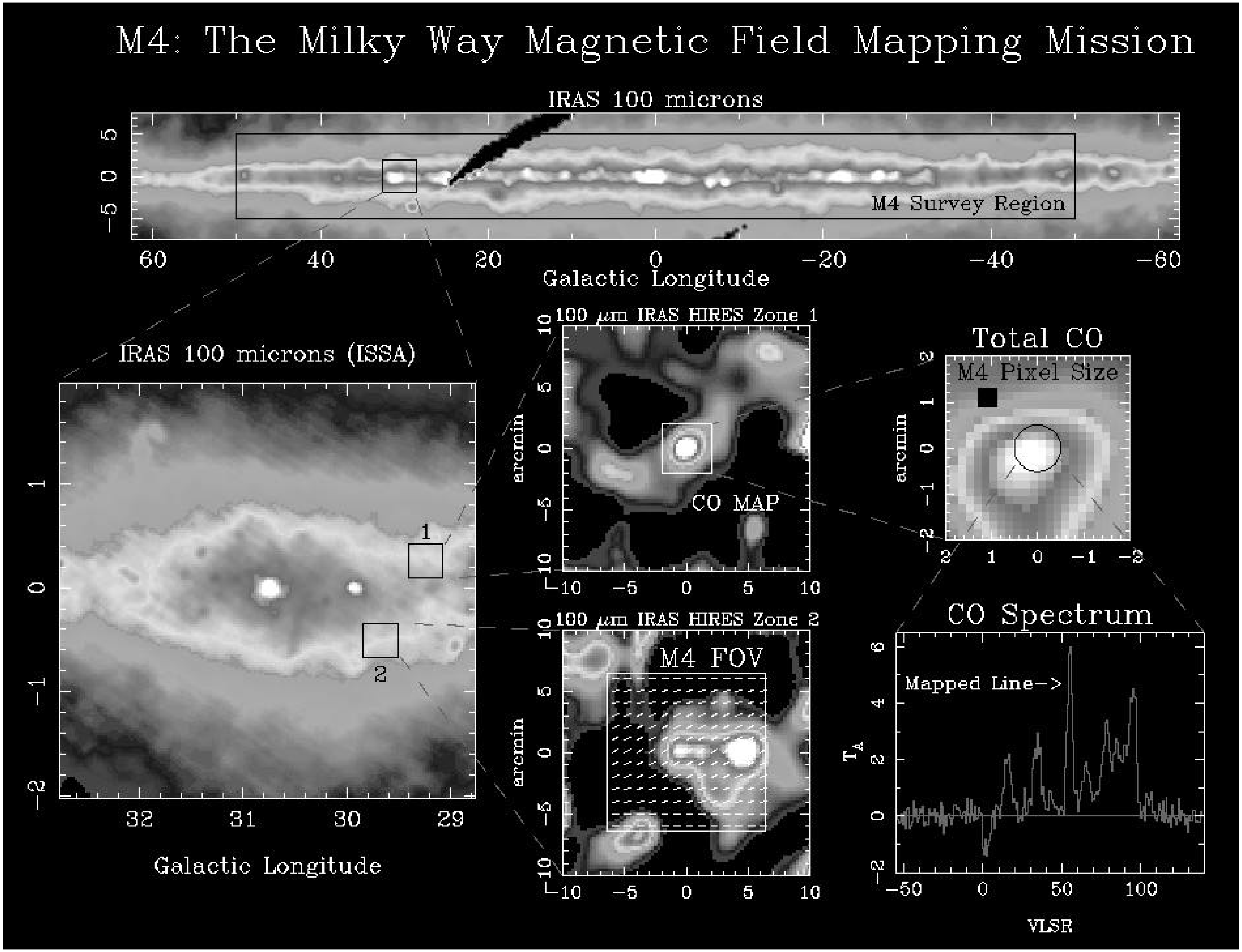

M4: The Milky Way Magnetic Field Mapping Mission
IRAS 100 μm
M31
M4 Survey Region
Oph/Sco Clouds
NCP Cirrus
−50
0
50
150
100
50
0
−50
−100
−150
Galactic Longitude



Sickle
(60 μm)
Thermal Arcs
(100 μm)
Non-Thermal
filaments
50 km/s
(350 μm)
Dust Ring
(350 μm)
20 km/s
(350 μm)
The University of Chicago
40′
44′
48′
52′
56′
−29°00′
−29°04′
Declination (1950)
17h43m40s
20s
43m0s
40s
20s
Right Ascension (1950)

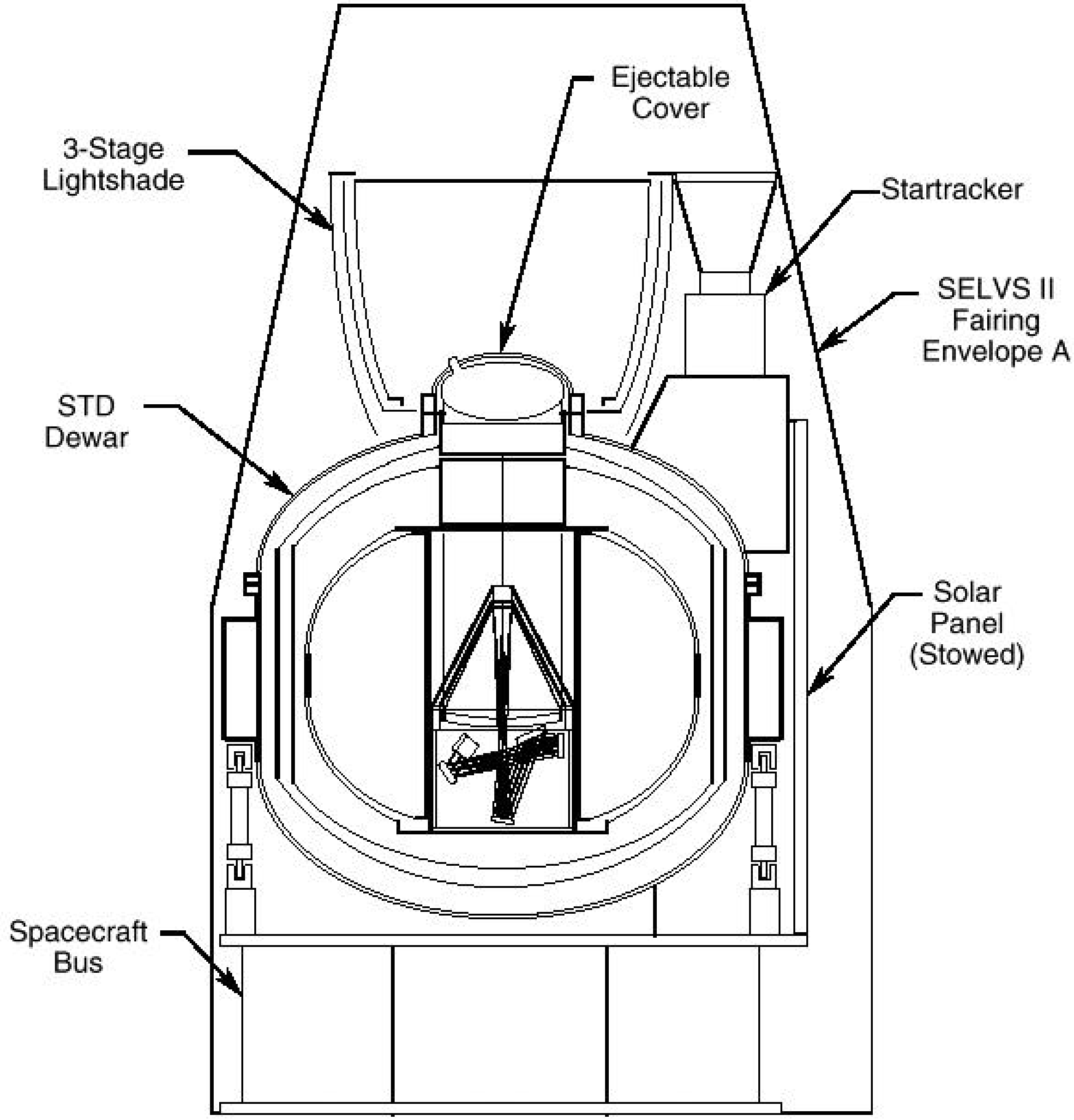


1/2000th of the Survey Area
-28° 30'
-28° 45'
-29° 00'
DEC
M4 Primary Beam
17h 44m
17h 43m
17h 42m
RA

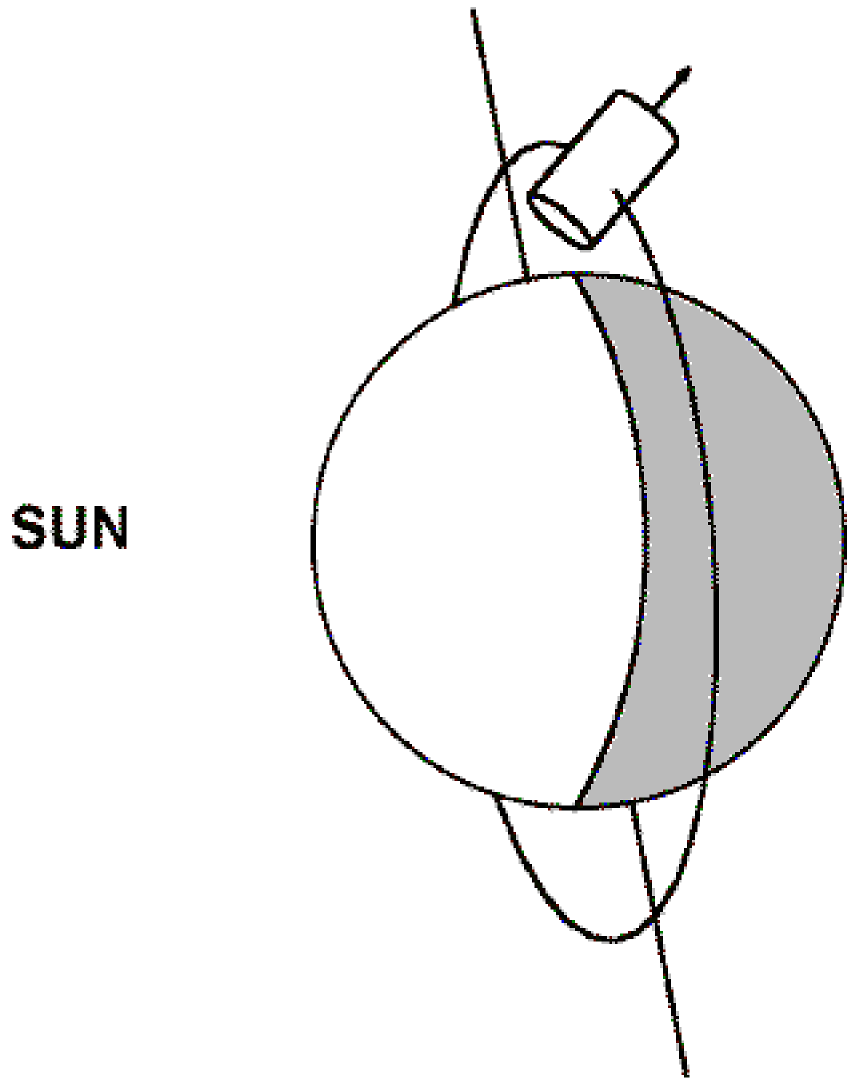

M4: The Milky Way Magnetic Field Mapping Mission
IRAS 100 microns
M4 Survey Region
Galactic Longitude
IRAS 100 microns (ISSA)
1
2
Galactic Longitude
100 μm IRAS HIRES Zone 1
CO MAP
arcmin
100 μm IRAS HIRES Zone 2
M4 FOV
arcmin
Total CO
M4 Pixel Size
arcmin
CO Spectrum
Mapped Line->
T_A
VLSR

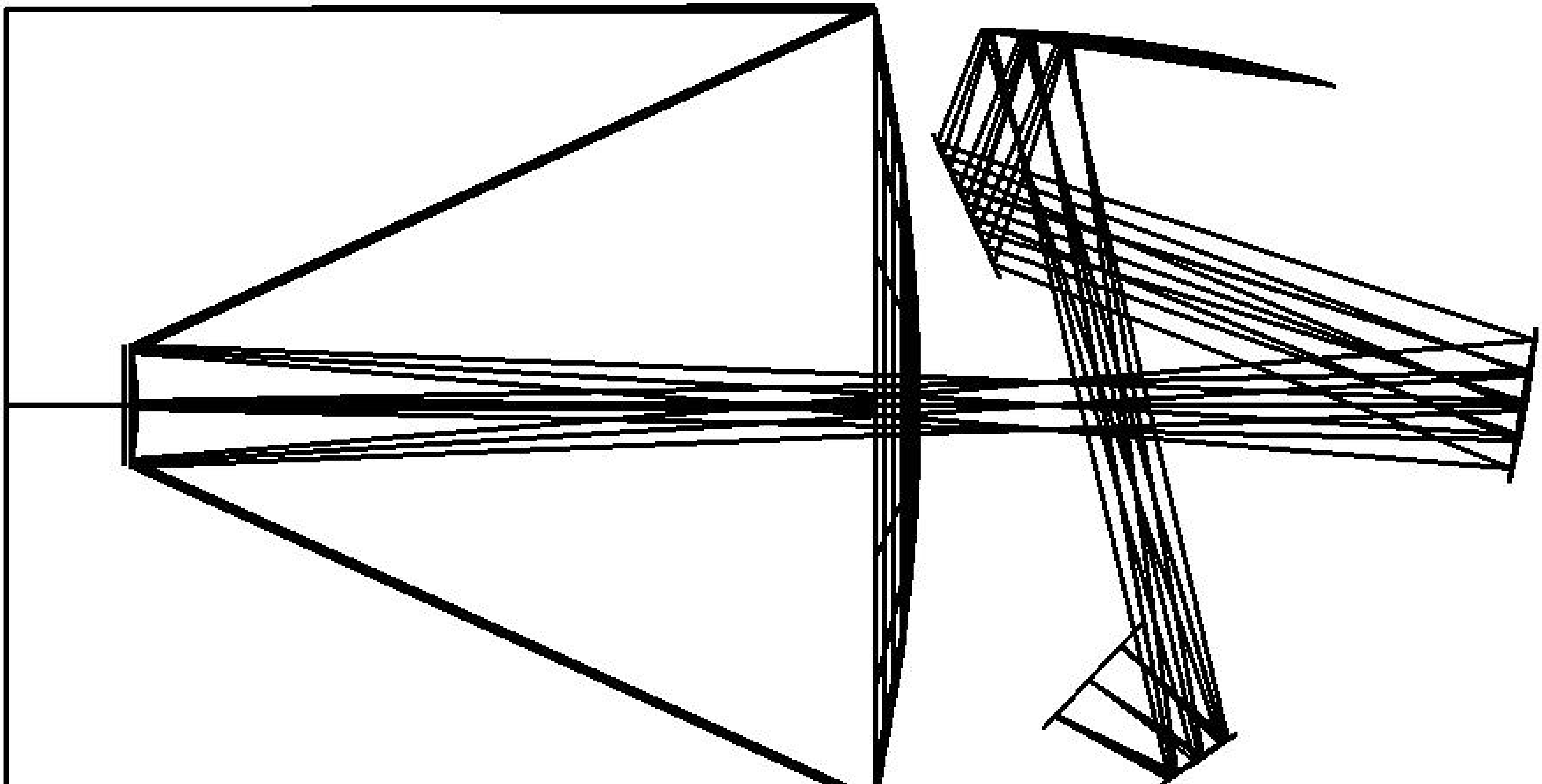
M4 Sensitivity Estimates for +/- 0.12% Polarization (per pixel)

Survey Region	longitude	latitude	Zody Background (MJy/sr)	Galactic Dust Background (MJy/sr)	M4 NESB (MJy/sr/ Hz)	Target Surface Brightness	Integration Time for S/N=600
Galactic Center	0	0	14	20,000	12.0	20,000	zip
Galactic Plane	25	0	10	2,400	4.1	2,400	1.1s
	25	5	9	330	0.8	330	38s
	50	0	6	35	0.5	35	73s
Sco/Oph	Oph core		15	40	0.6	300-2,400	0-1.4s
	Dark Filaments		15	40	0.6	5-80	20s-87min
IR Cirrus	Bright Cores		4.6	0.2	0.2	8	225s
	Filaments (2x2 pixel)		4.6	0.2	0.2	1-3	640s-97min
M31	Cores		6.4	3.7	0.3	40	20s
	Spiral Arms		6.4	3.7	0.3	3-14	165s-60min



Ball Aerospace
& Technologies Corp.
Aerospace Systems Division


SUN



WIRE FRAME

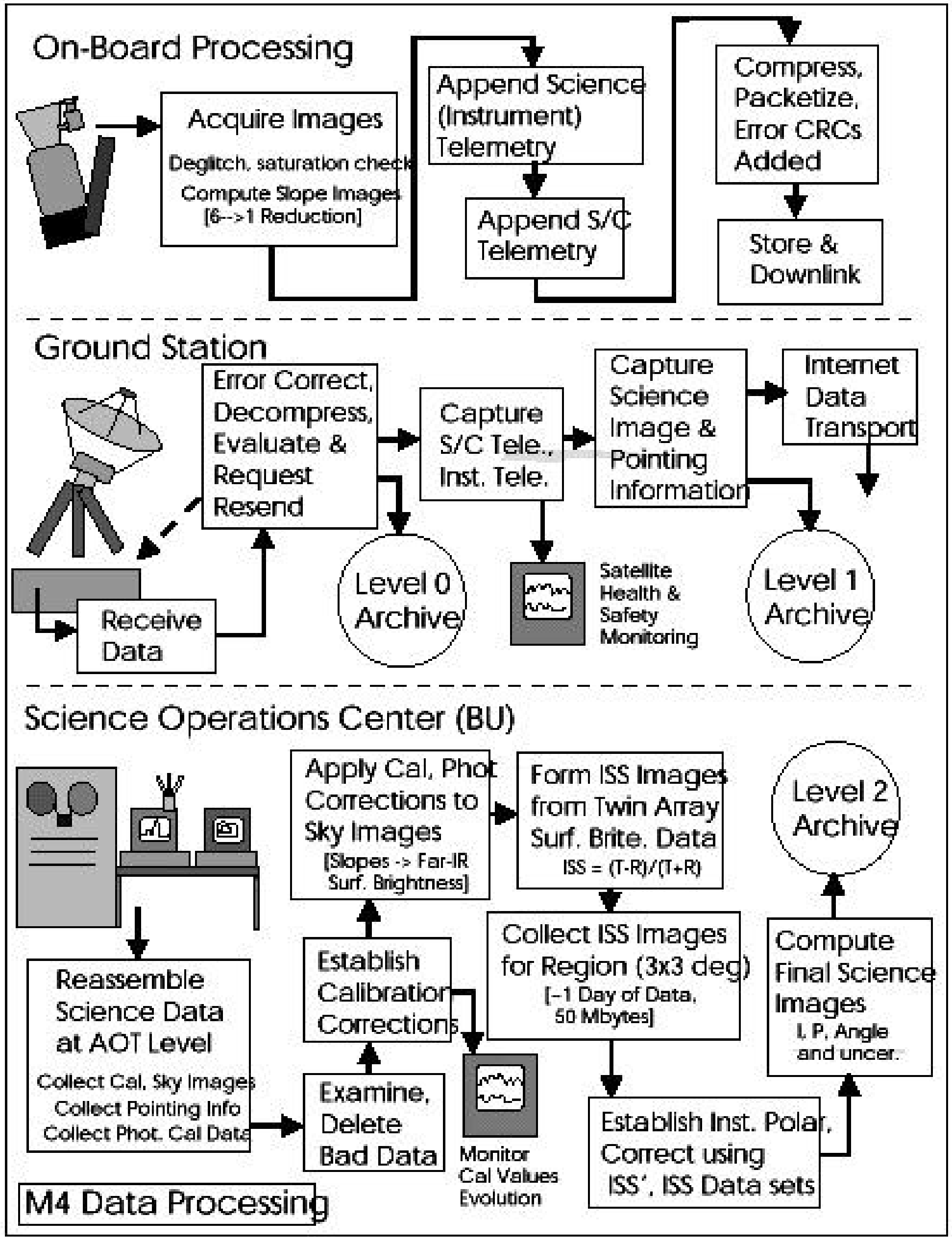
M4 (20 CM) TELESCOPE AND INSTRUMENT OPTICS
MON OCT 11 1999

MINNESOTA ASTRONOMY
TERRY JAY JONES

C:\ZEMAX\DATA\M4\M4_20_TRANS_TRY2.ZMX

To Move or Not to Move

- No moving parts is good.
- Rotating spacecraft near the Earth is a problem.
- One simple moving part is not impossible, but it is expensive (several million extra).
- Not rotating the spacecraft relieves the thermal shielding requirements and improves the observing efficiency somewat.
- Rotating a waveplate greatly improves data reduction.


On-Board Processing
Acquire Images
Deglitch, saturation check
Compute Slope Images
[6-->1 Reduction]
Append Science (Instrument) Telemetry
Append S/C Telemetry
Compress, Packetize, Error CRCs Added
Store & Downlink
Ground Station
Error Correct, Decompress, Evaluate & Request Resend
Capture S/C Tele., Inst. Tele.
Capture Science Image & Pointing Information
Internet Data Transport
Receive Data
Level 0 Archive
Satellite Health & Safety Monitoring
Level 1 Archive
Science Operations Center (BU)
Apply Cal, Phot Corrections to Sky Images
[Slopes -> Far-IR Surf. Brightness]
Form ISS Images from Twin Array Surf. Brite. Data
ISS = (T-R)/(T+R)
Level 2 Archive
Reassemble Science Data at AOT Level
Collect Cal, Sky Images
Collect Pointing Info
Collect Phot. Cal Data
Establish Calibration Corrections
Collect ISS Images for Region (3x3 deg)
[~1 Day of Data, 50 Mbytes]
Compute Final Science Images
I, P, Angle and uncer.
Examine, Delete Bad Data
Monitor Cal Values Evolution
Establish Inst. Polar, Correct using ISS', ISS Data sets
M4 Data Processing

What M4 Could Not Do

- Resolve the magnetic field geometry in dense cloud cores.
- Survey the entire galactic plane.
- Measure magnetic field strength.
- Work longward of 100 microns.

Complimentary with SOFIA

- SOFIA will have 12x the spatial resolution but it will be less sensitive than M4.
- SOFIA will have to ‘chop’, so it is limited to bright, compact regions, M4 is not.
- SOFIA will be unable to connect the MC core to the general ISM, M4 will.
- M4 will provide targets for SOFIA.

The Task Ahead

- Define the science.
- Confine the science goals by technical reality.
- Articulate the resulting science case as best as possible.

Polarimetry with ISO: Lessons Learned, Enabled Science

R. J. Laureijs and B. Schulz

ISO Data Centre, Madrid
19-Oct-1999

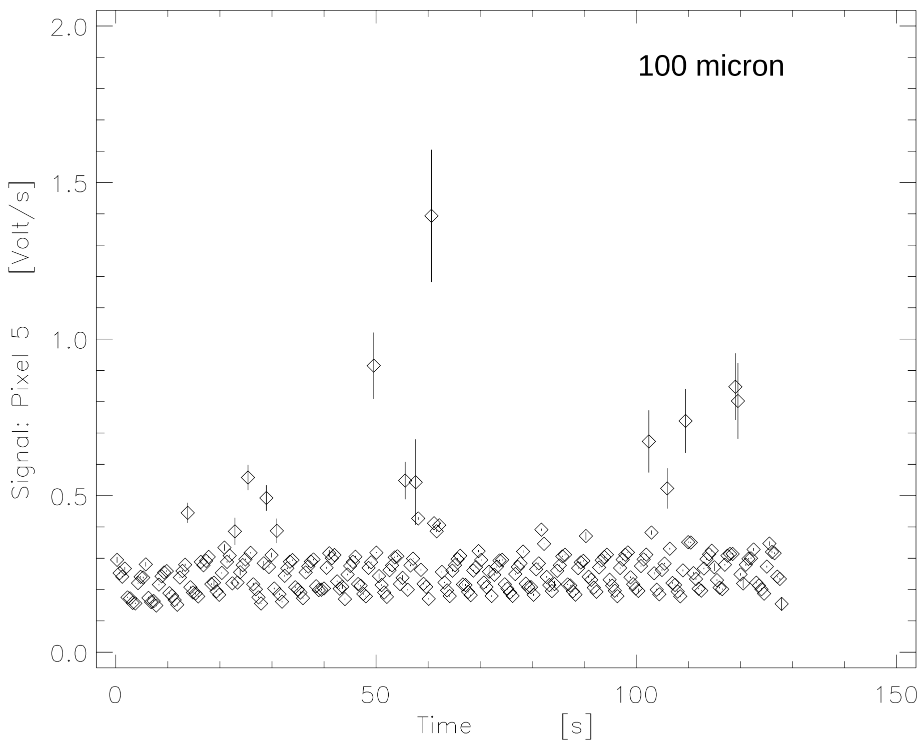
- some historical issues
- search for best observing mode
- .....calibration...
- if we could do it again

Some historical issues

- ISOPHOT and ISOCAM polarisation: "desirable".
- Minimal support from ISO development.
  Preparations and planning were performed by instrument team member and 1 resident SOC astronomer per instrument.
- Operations to be performed using the calibration uplink system (CUS).
  Advantage: full flexibility,
  disadvantage: need instrument specialist.
- Data entry interface software written by instrument team member.
- During operations no formal support, "workload permitted".
- Data processing using Interactive Analysis.
- Present results only achieved due to longer lifetime of ISO.

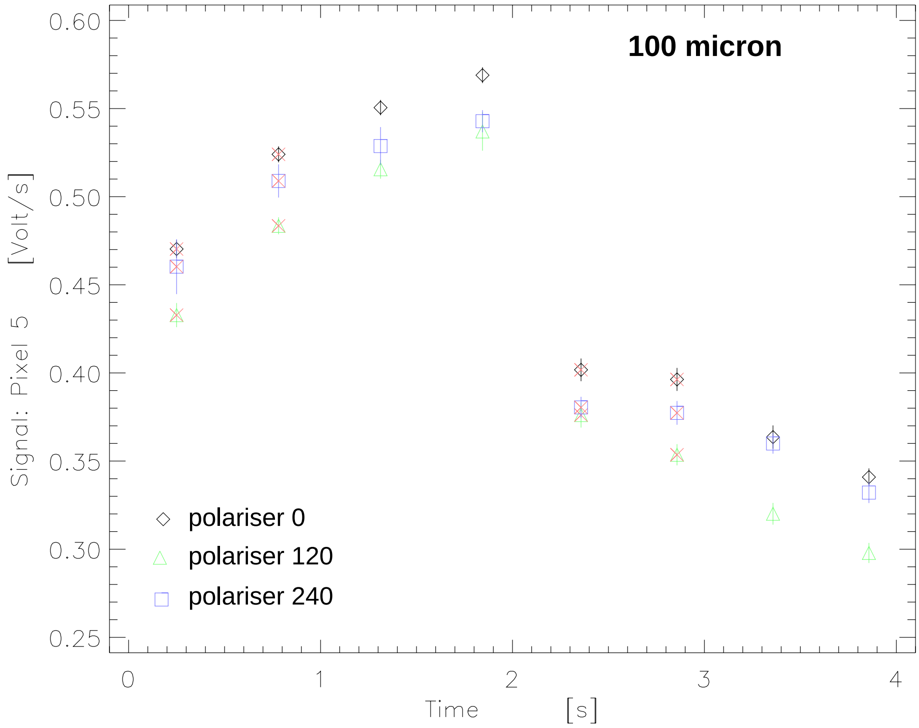
Search for best observing mode (1)

- "unexpected" in-orbit performance of detectors
  1. higher noise for C100 and P3 detectors (Ge:Ga material)
  2. detector transients rendered measurement times less than 32 s unfeasible
  3. transients difficult to model/predict with sufficient accuracy
- need long and stable integrations



3C273, C100 chopped, polariser 0

Search for best observing mode (2)

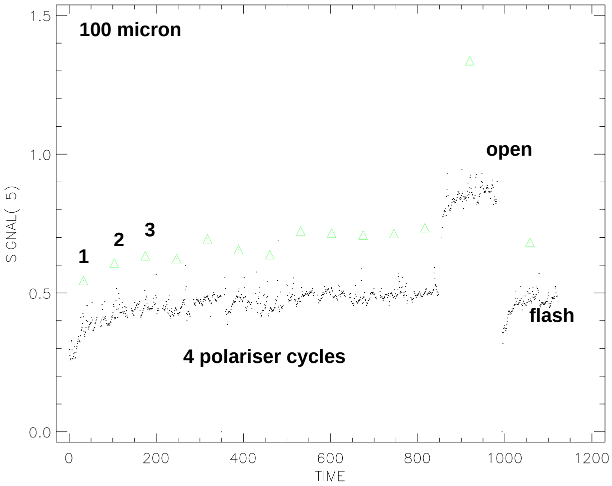


3C273, C100 processed chopped

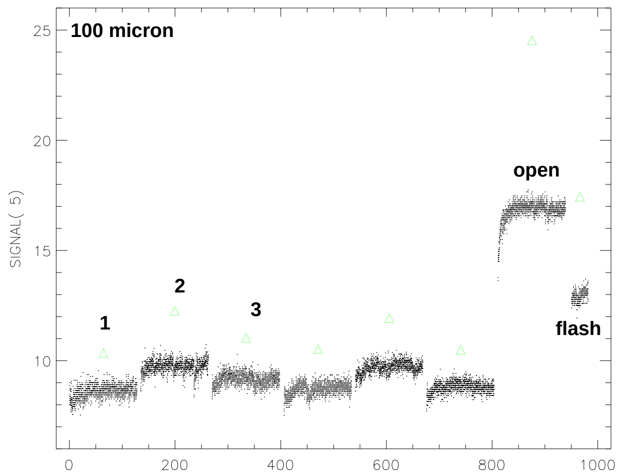
Example of recently processed chopped measurements according latest processing algorithms.

New deglitching techniques and additional calibration could be used to interpret the data. Requires lots of humanpower and a sufficient amount of calibration/test data.

Search for best observing mode (3)



3C279, C100 staring



Centaurus A, C100 staring

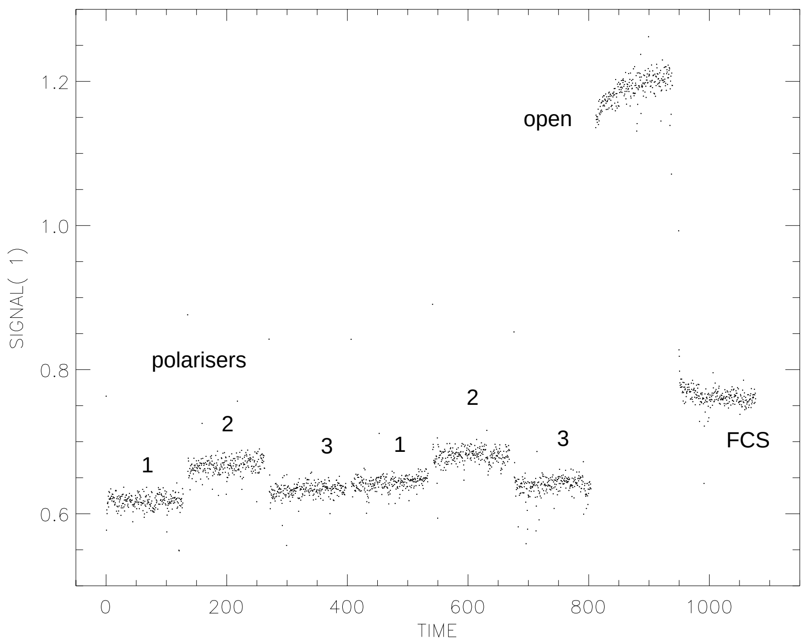
Examples of C100 (Ge:Ga detector) signals for a weak (3C279) and a strong (Centaurus A) source.

Search for best observing mode (4)

Final design of ISOPHOT polarisation mode

- choose best detectors and most suitable filters:
  P2 (Si:B) with 25 micron filter
  C200 (stressed Ge:Ga) with 170 micron filter
- long fixed integration time per polariser cycle
- avoid upsetting the detector: open and FCS measurement at the end
- impose redundancy in observing strategy.

Price: (1) long integration times per pointing and (2) intensive uplink support for fixed time scheduling.



Search for best observing mode (5)

Instrumental features in CAM polarisation:

1. polariser change caused source displacement on the array
2. detector transients; however, transients only affect the absolute photometric accuracy
3. dead column, 2×2 raster maps required.

Final design of ISOCAM polarisation mode for extended sources:

- change polariser *after* completion small raster map
- perform repointing after each polariser change

...Calibration...

One needs to be able to have the:

- firm set of polarised and unpolarised calibrators;
- ability to repeat observations at (ir)regular time intervals;
- ability to derive the instrumental, sky, and source polarisation early during operations;
- a flexible uplink/analysis system to test new observing procedures.

If we could do it again....

Apart from sufficient **expert** human resources, we would:

- like to have ground tests experience available during operations;
- polariser throughputs and efficiencies;
- pool of readily available calibration standards;
- short uplink turn-around times;
- be prepared to change the entire observing strategy.

Instrument Design in the Light of the ISOPHOT Experience

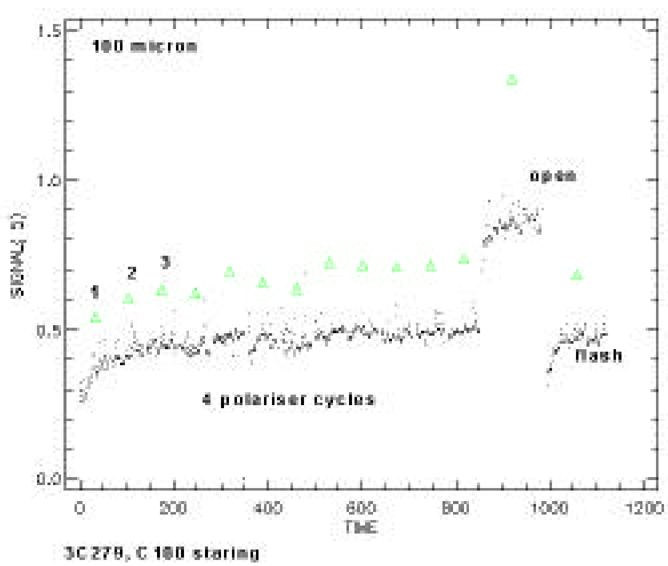
Bernhard Schulz, Rene Laureijs
ISO Data Centre, ESA

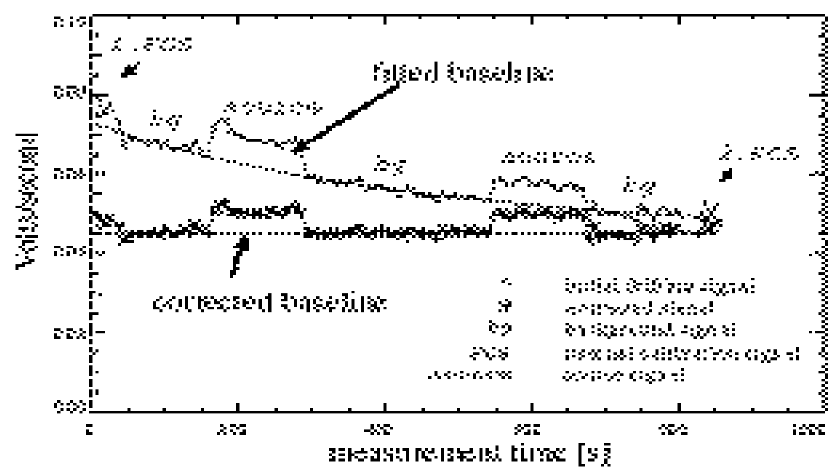
- Noise
  - Detector noise increased in orbit w.r.t. lab. meas.
  - Characteristics difficult to match with theory.
  - Equal spacing of NDRs allowed to recover from glitches.
  - Best Ge:Ga curing with bias boost and IR-flashing.

Detector	Material	Bias [V]	NEP (dark) [W/sqrt(Hz) pre-flight	NEP (dark) [W/sqrt(Hz) in-flight	Dark [e/s] pre-flight	Dark [e/s] in-flight
C200	Ge:Ga (s)	0.08	1.20E-17	2.40E-17	1869	4000
C100	Ge:Ga	0.18	8.70E-18	2.61E-17	7471	25000
P3	Ge:Ga	0.25	3.50E-18	3.50E-16	123	19700
P2	Si:B	10	2.20E-16	4.40E-16	3825	5960
P1	Si:Ga	90	1.60E-16	1.76E-16	1595	1460
S2	Si:Ga	37	1.50E-15	1.65E-15	<500	<500
S1	Si:Ga	37	6.00E-16	6.60E-16	<500	<500

- System Linearity
  - De-biasing: CRE gain not matched to low biases.
  - Pre-amplifiers show non-linear transfer function.
  - Readout patterns influence signals (reset interval correction, clock frequency dependency).
  - Detector responsivity depends on flux.
  - FCS calibration scheme with many cal.-standards covering flux range enabled linearisation.
  - Missing early photometric assessment at assembly level.

- Stability
  - No stable operation of detectors (switching, heaters).
  - Switch-on effect (longterm transient).
  - Si:Ga very stable over long periods, Ge:Ga not.
  - Actuator flashing induces transients (changed in LWS).
  - Ge:Ga det. show sudden changes in signal.
  - Redundancy in meas. sequences very important.





- AOT-Design
  - Was started when laboratory people started to understand how to use detectors.
  - Lab team was not sufficiently involved.
  - Lab. design not close enough to astron. requirements.
  - AOTs make instrument easy to use but degrade performance (exec. Time, stability).
  - Number of AOTs increases parameter space further.
  - Time requirements are actually determined by transient timeconstants and not by S/N.
  - Longer meas. sequences (multi filter, multi aperture) are "fixed" only by one cal. measurement.

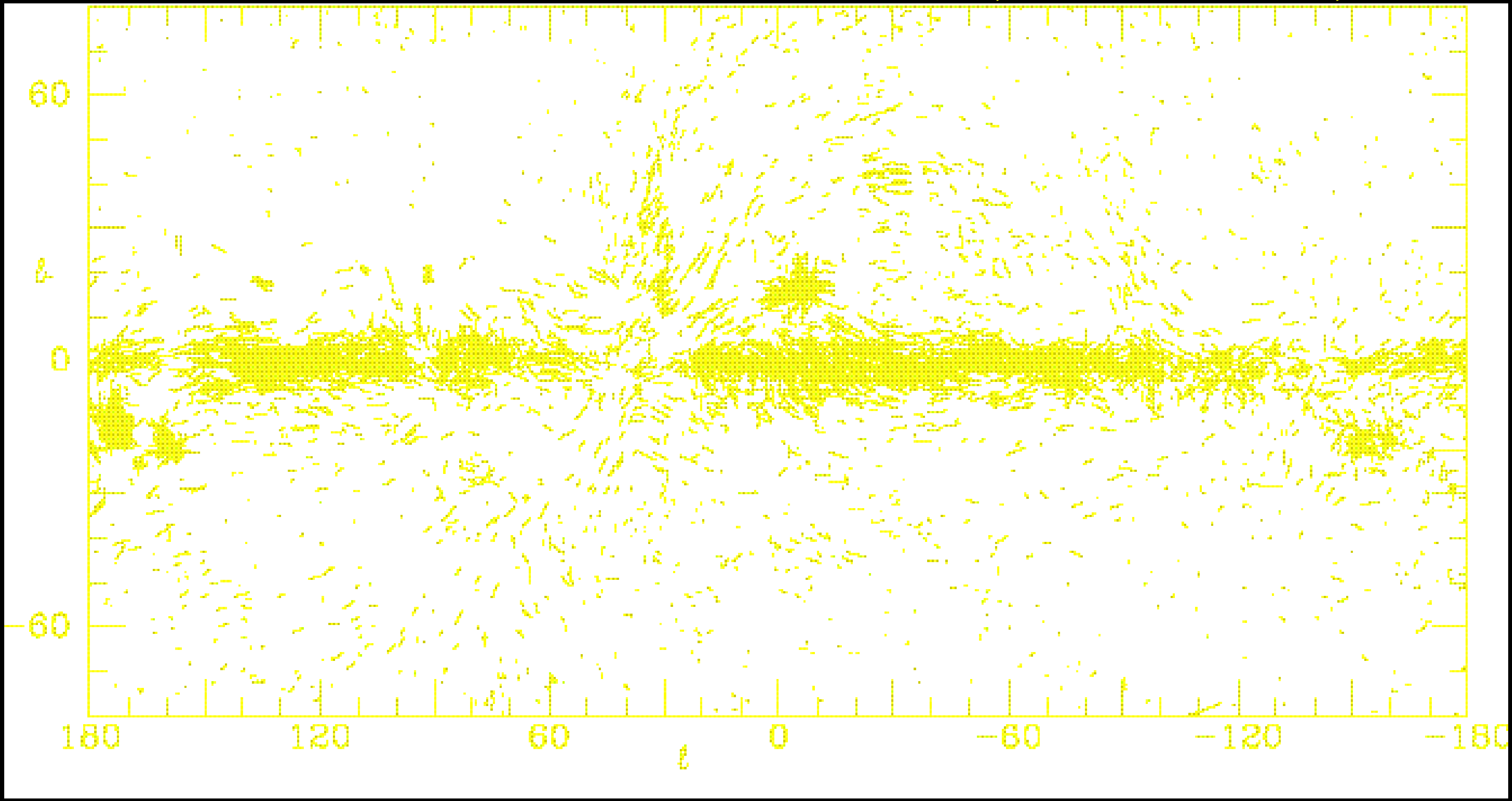
- External Straylight (Sun, Earth, Moon)
  - No problem for ISO but important if attitude changes (spacecraft roll).
- Calibration Strategy
  - Possible configurations led to large parameter space.
  - Instrument modelling can limit parameter space, but at the cost of systematic errors.
  - Highest accuracy only achieved by empirical approach.
  - Hope for better understanding in the future was mostly disappointed.

Introduction to M4 Science

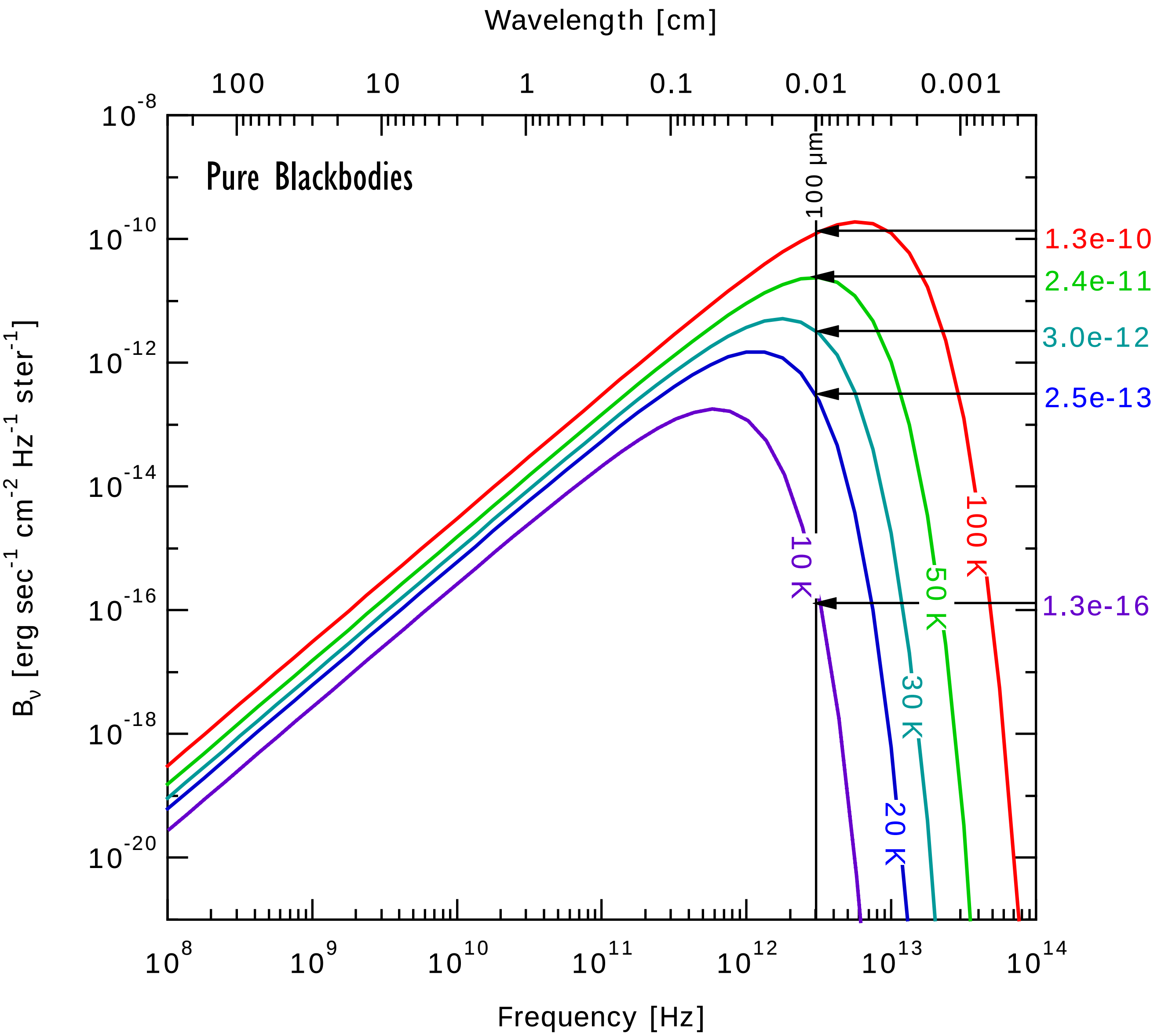
- Observe 95 μm Polarized Radiation
- Map the "Magnetic Field of the Milky Way" (Central 100 degrees in l and 10 degrees in b)
  - Technique for Constructing 3-D Field Relies on FIR/CO Associations
- Detailed Studies of B in selected Supershells (Cirrus), Star-forming Regions, and External Galaxies

The 20th Century Magnetic Field of the Milky Way

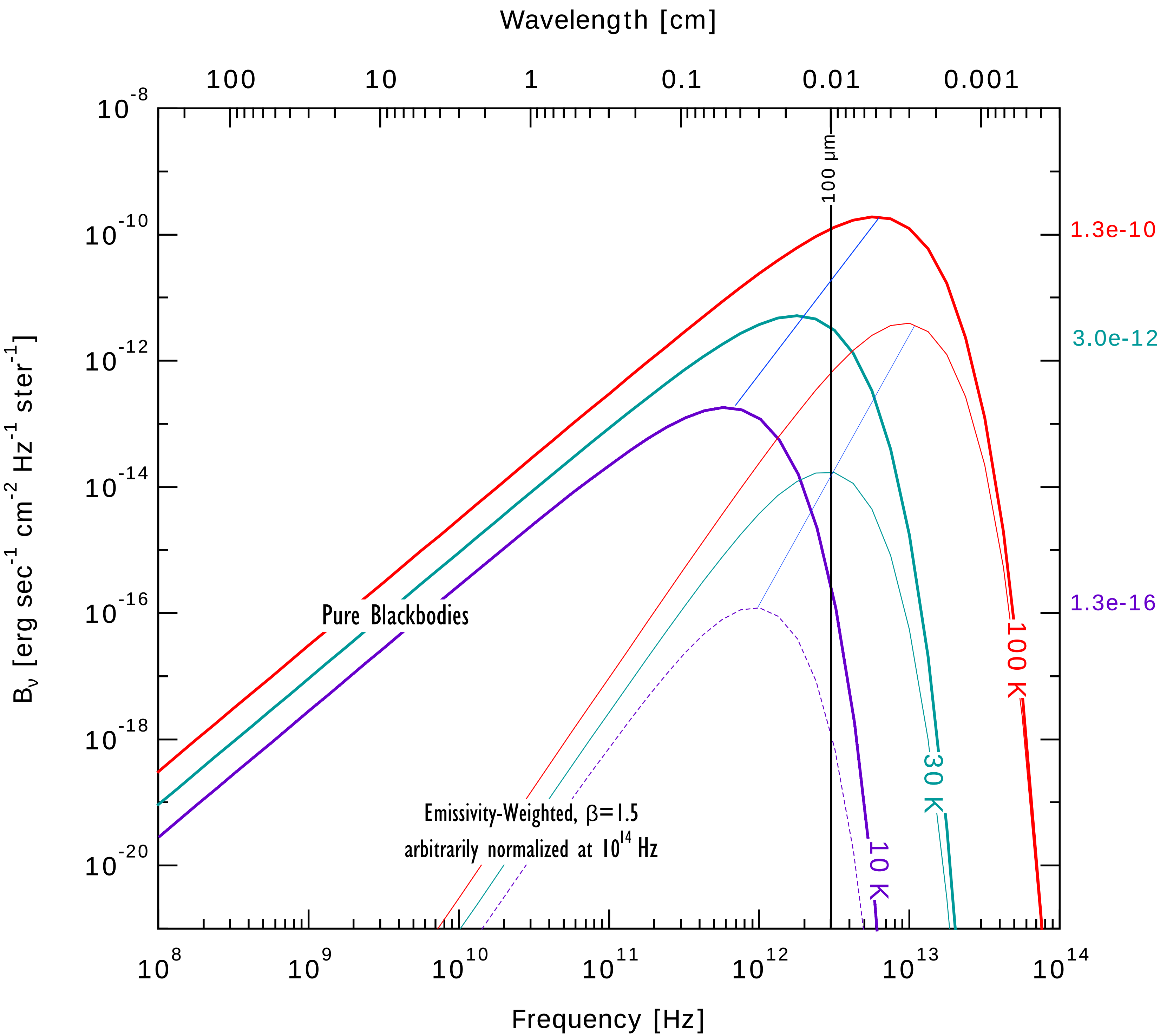
Serkowski, Mathewson & Ford, et al.

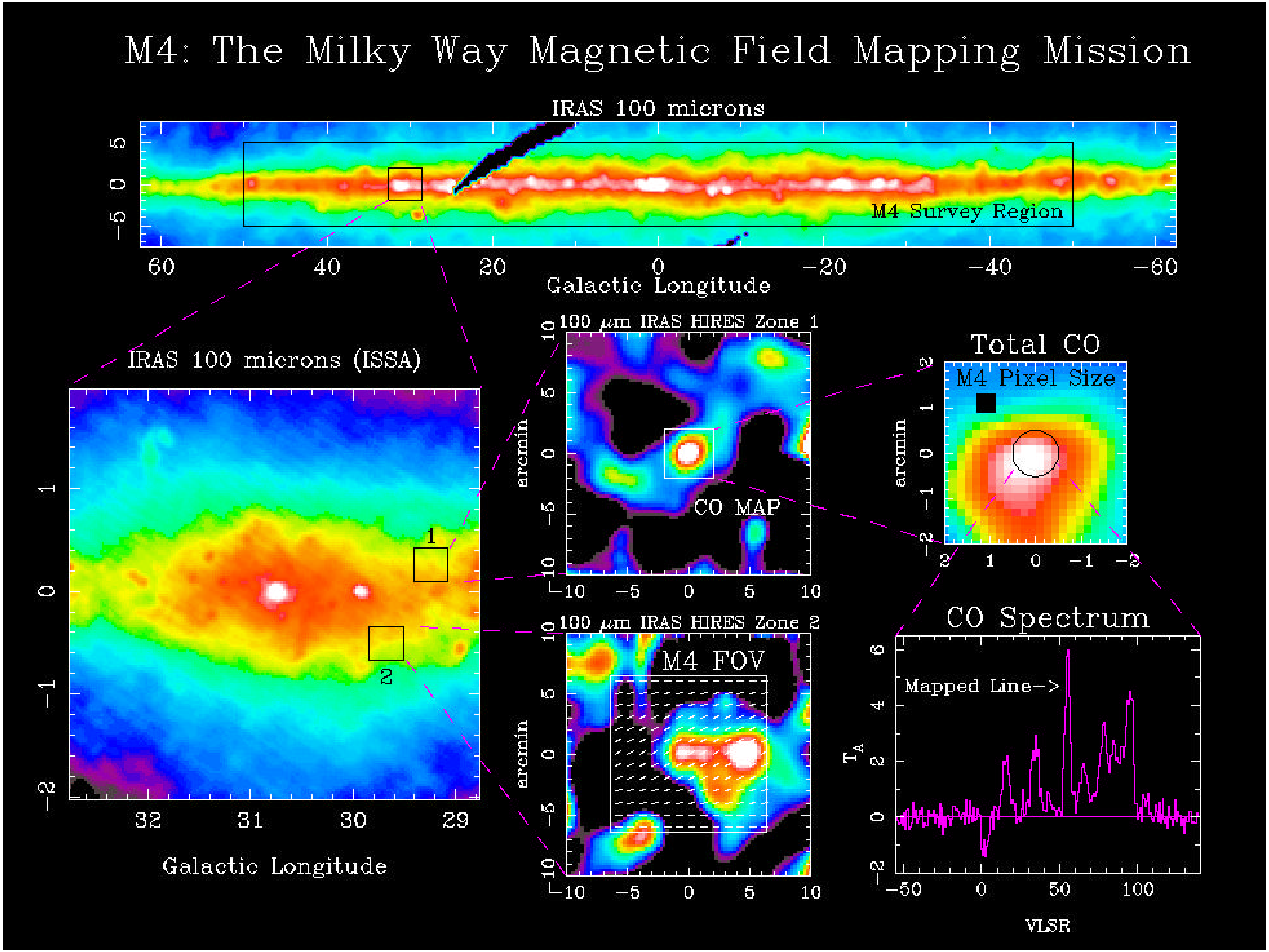


See Heiles for more, later.



Wavelength [cm]
100
10
1
0.1
0.01
0.001
Pure Blackbodies
100 µm
1.3e-10
2.4e-11
3.0e-12
2.5e-13
1.3e-16
100 K
50 K
30 K
20 K
10 K
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
B_ν [erg sec^{-1} cm^{-2} Hz^{-1} ster^{-1}]
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Frequency [Hz]


Wavelength [cm]
100
10
1
0.1
0.01
0.001
100 μm
1.3e-10
3.0e-12
1.3e-16
Pure Blackbodies
100 K
30 K
10 K
Emissivity-Weighted, β=1.5
arbitrarily normalized at 10^14 Hz
Bν [erg sec^-1 cm^-2 Hz^-1 ster^-1]
Frequency [Hz]


M4: The Milky Way Magnetic Field Mapping Mission
IRAS 100 microns
M4 Survey Region
Galactic Longitude
IRAS 100 microns (ISSA)
Galactic Longitude
100 μm IRAS HIRES Zone 1
CO MAP
arcmin
100 μm IRAS HIRES Zone 2
M4 FOV
arcmin
Total CO
M4 Pixel Size
arcmin
CO Spectrum
Mapped Line->
T_A
VLSR

Milky Way Polarimetric Discoveries 1997-99

summarized by

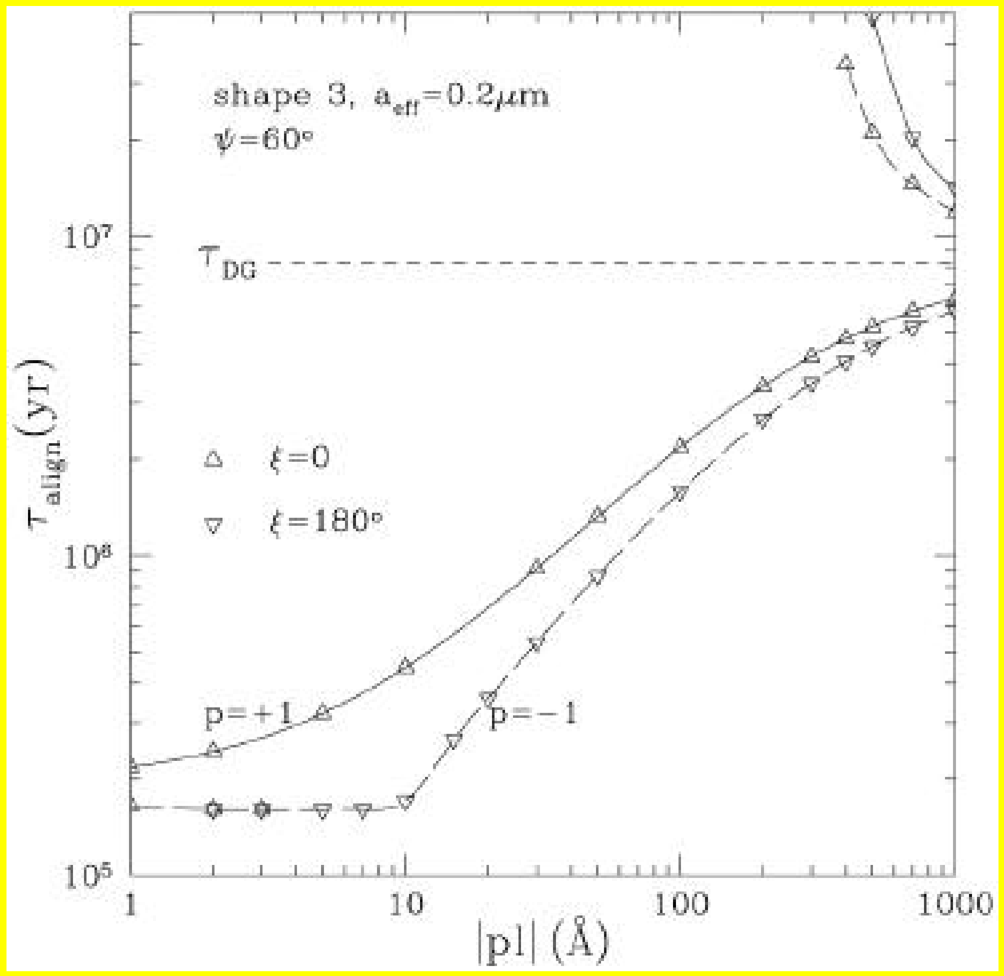
Alyssa Goodman
Harvard University

Grain Alignment

- Role of Radiative Torques (Draine, Weingartner, Lazarian)
- Spectral Dependence of Thermal Emission Polarization (Hildebrand et al. 1999; *see Dowell*)
- Global Polarization-Extinction Relation (Arce et al. 1998; Goodman 1999)

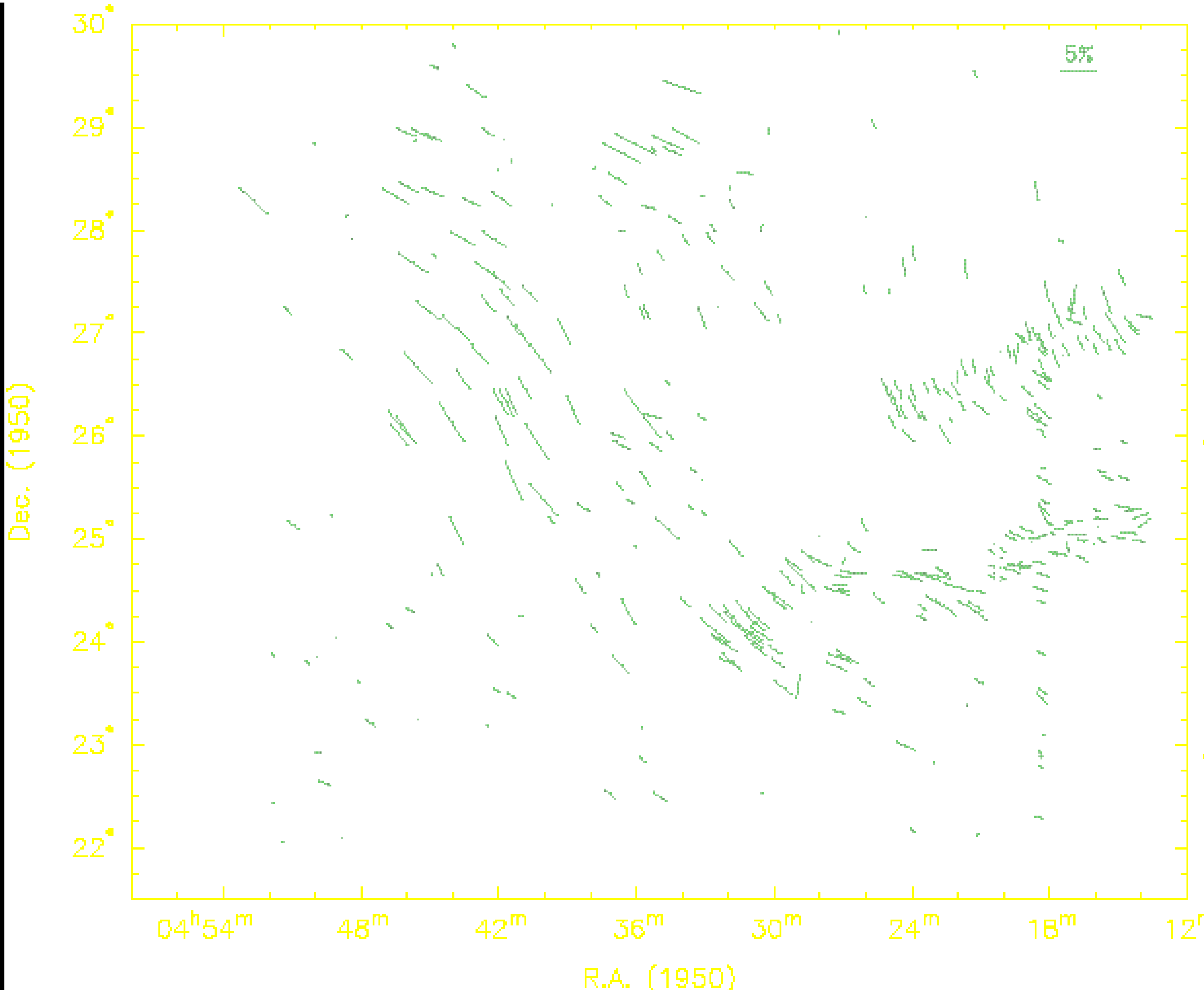
Radiative Torques on “Helical” Grains

- Non-Davis-Greenstein processes likely dominate (*see Draine, Weingartner, Lazarian*)
- Rapid alignment of grains in less than dim regions

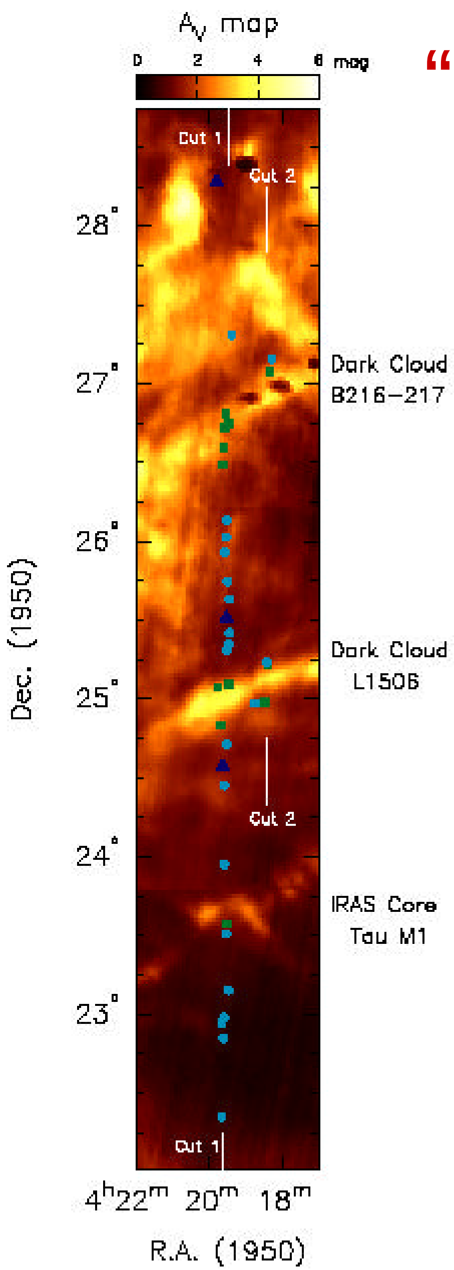


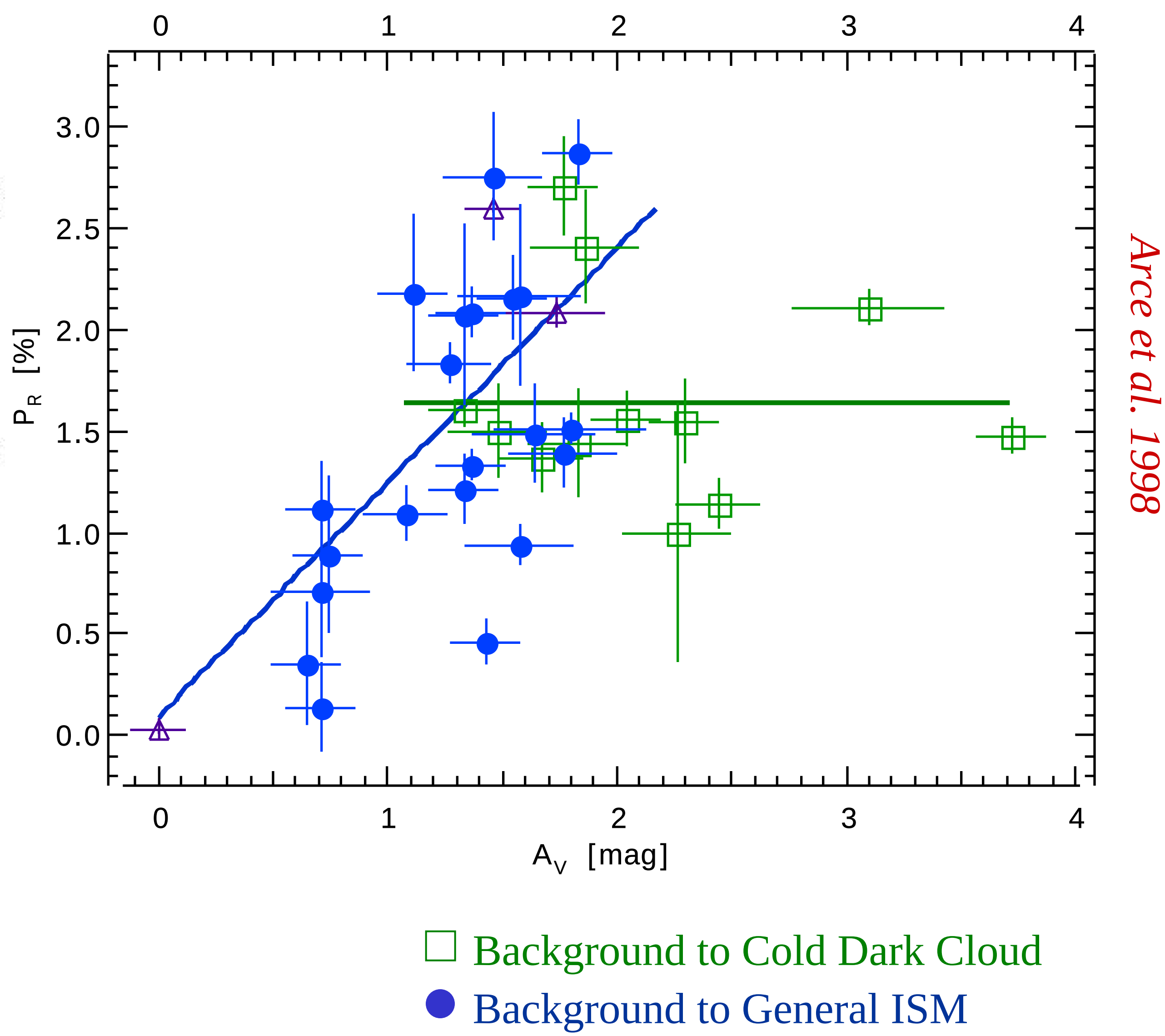
Draine & Weingartner, 1997

Dark Cloud Complexes: 1-10 pc scales

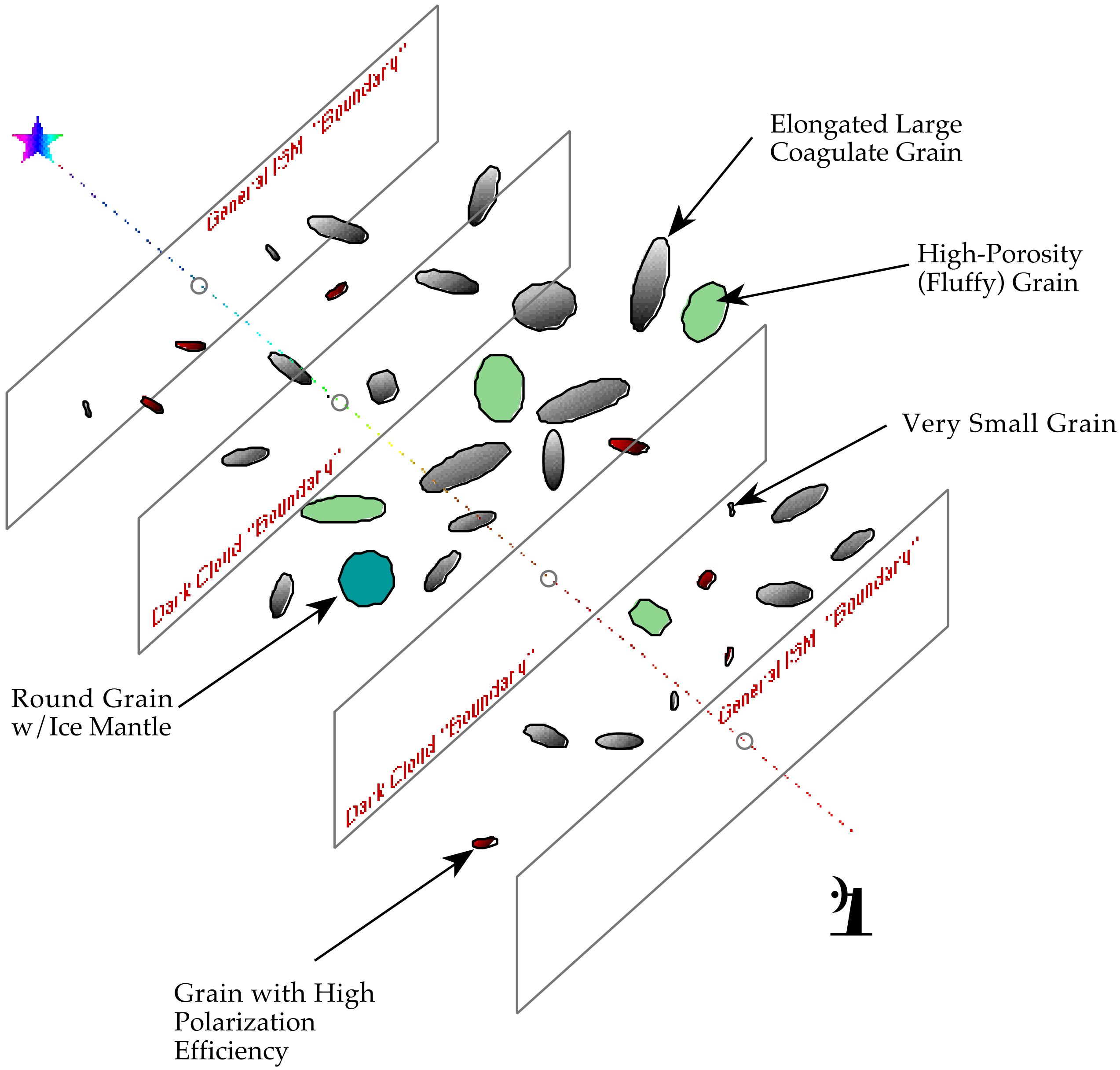


"Go no further than A_V~1.3 mag."





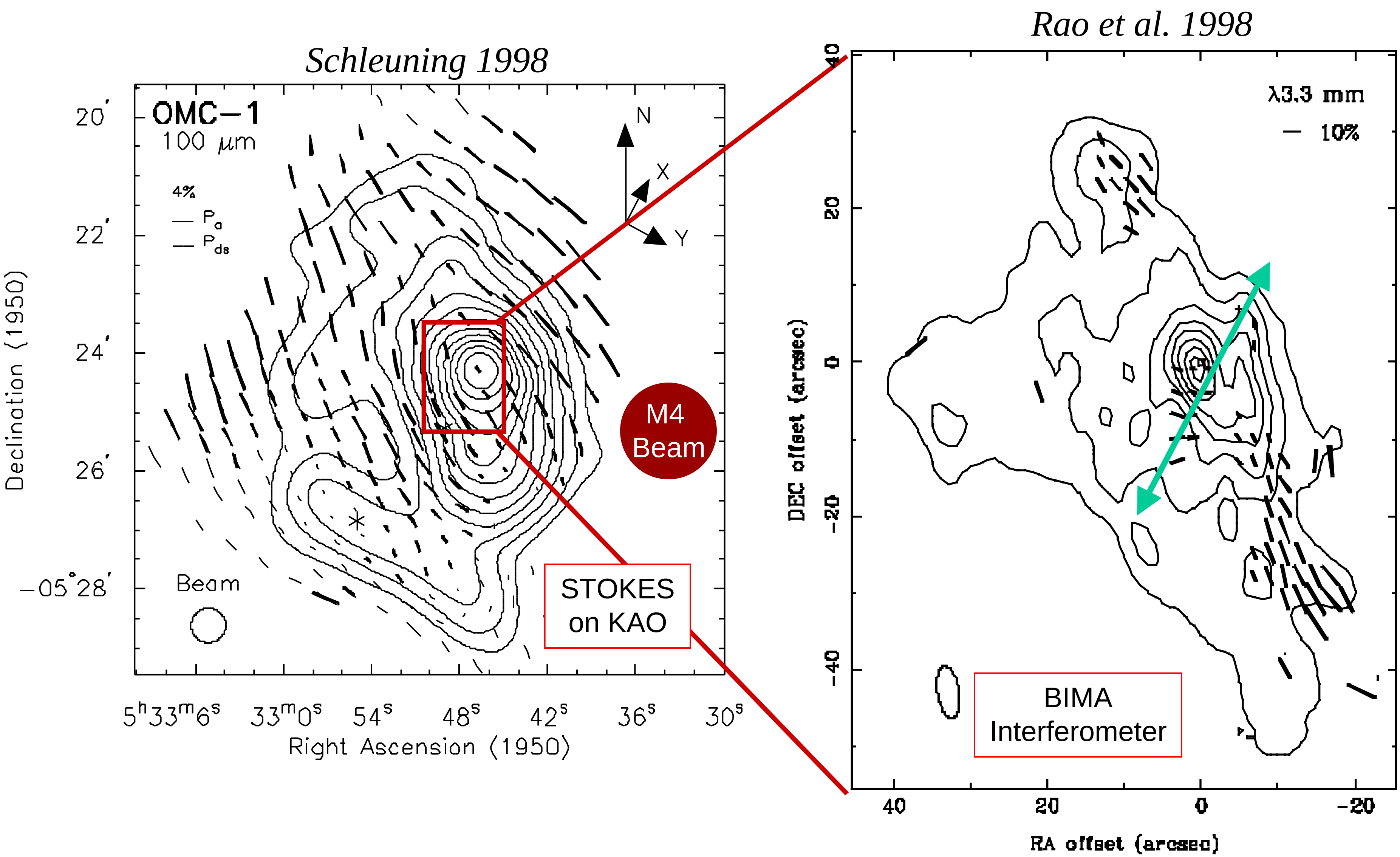
"Not All Grains are Created Equal"



Developments in Star-forming Regions

- Interferometric Polarimetry of Outflow/Disk Sources (OVRO: Akeson et al. 1996; BIMA: Rao et al. 1998; *see Myers*)
- Polarized Spectral-line Emission (BIMA: Girart et al. 1999)
- Sub-mm (SCUBA) Polarimetry of Massive, and now Low-Mass, SFRs (e.g. Matthews & Wilson 1999; *see Greaves*)

Zooming on Orion BN/KL



On a Galactic Scale

- Rand & Lyne (94) Pulsar RM/DM Mapping of **B**
- Reid & Menten update of Galactic **B** from H_2O Masers (in prep.)
- Heiles' Re-analysis of Galactic Plane Background Starlight Polarimetry Surveys *(see Heiles)*
- SCUBA Polarimetry of the Galactic Center (*see Greaves*)

On a Galactic Scale

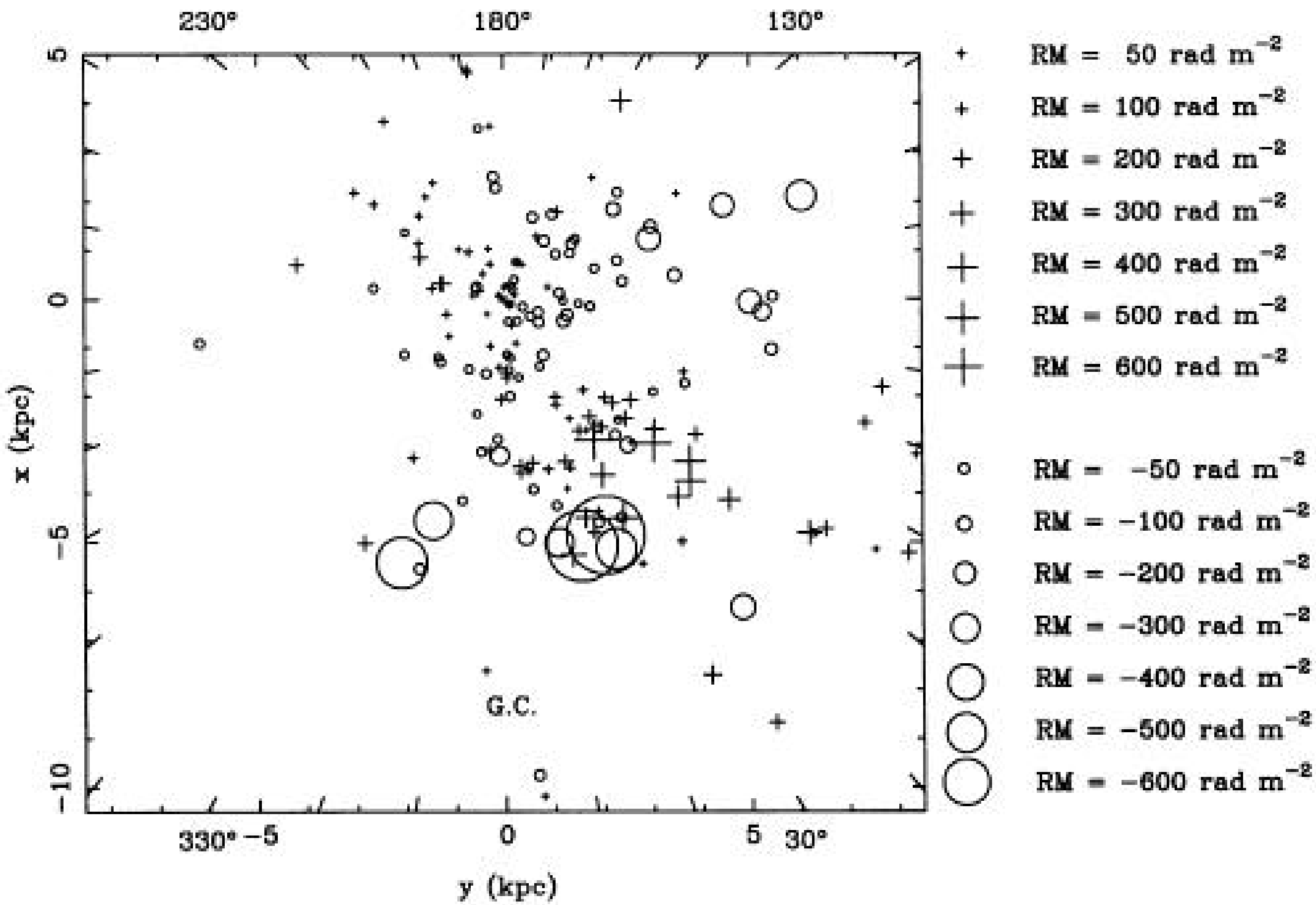


Figure 3. All but nine of the known RMs in a top view of the Galaxy, as in Fig. 2 (the remaining nine do not fit conveniently in the frame). Note the large amount of structure in this figure, with negative RMs found in directions around $l = 90°$ and $l = 330°$, and positive RMs in directions around $l = 270°$ and $l = 40°$. This structure suggests a field running toward $l \approx 90°$ in the Solar neighbourhood, but a reversed field in the inner Galaxy. At about 5 kpc from the Sun, in the range $0° < l < 30°$, the cluster of negative RMs suggests that the field reverses direction again between the Sun and these pulsars (see Fig. 6 for a sketch of a plausible Galactic magnetic field geometry). The new RMs greatly reinforce this suggestion.

Rand & Lyne 1994

On a Galactic Scale

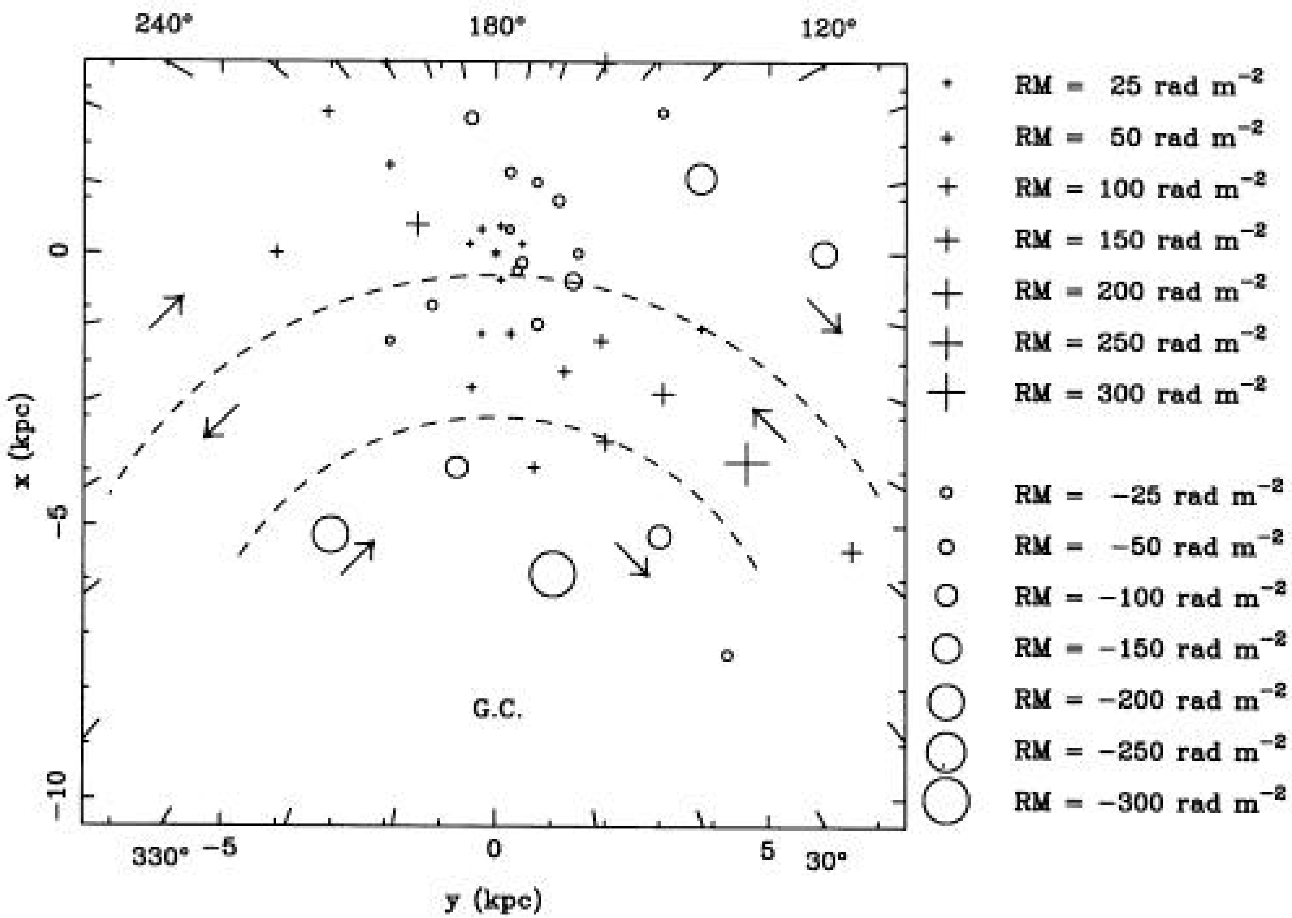


Figure 5. Values of RM averaged in 20° bins of longitude and in distance bins 0–1 kpc, 1–2 kpc, 2–3 kpc, 3–5 kpc, 5–7 kpc and 7–10 kpc. Overlaid is a sketch of the best-fitting ring model of the Galactic magnetic field, showing the two reversals.

Rand & Lyne 1994

On a Universal Scale

- Connection to CMB Polarimetry *(see Lazarian)*
  - Our signal is their "foreground," and we have MUCH better polarimetric sensitivity and resolution.
  - MAP launch November 2000
- Any light on galactic dynamo issues/origin of galactic fields *(ask Zweibel)*?

What can we expect?

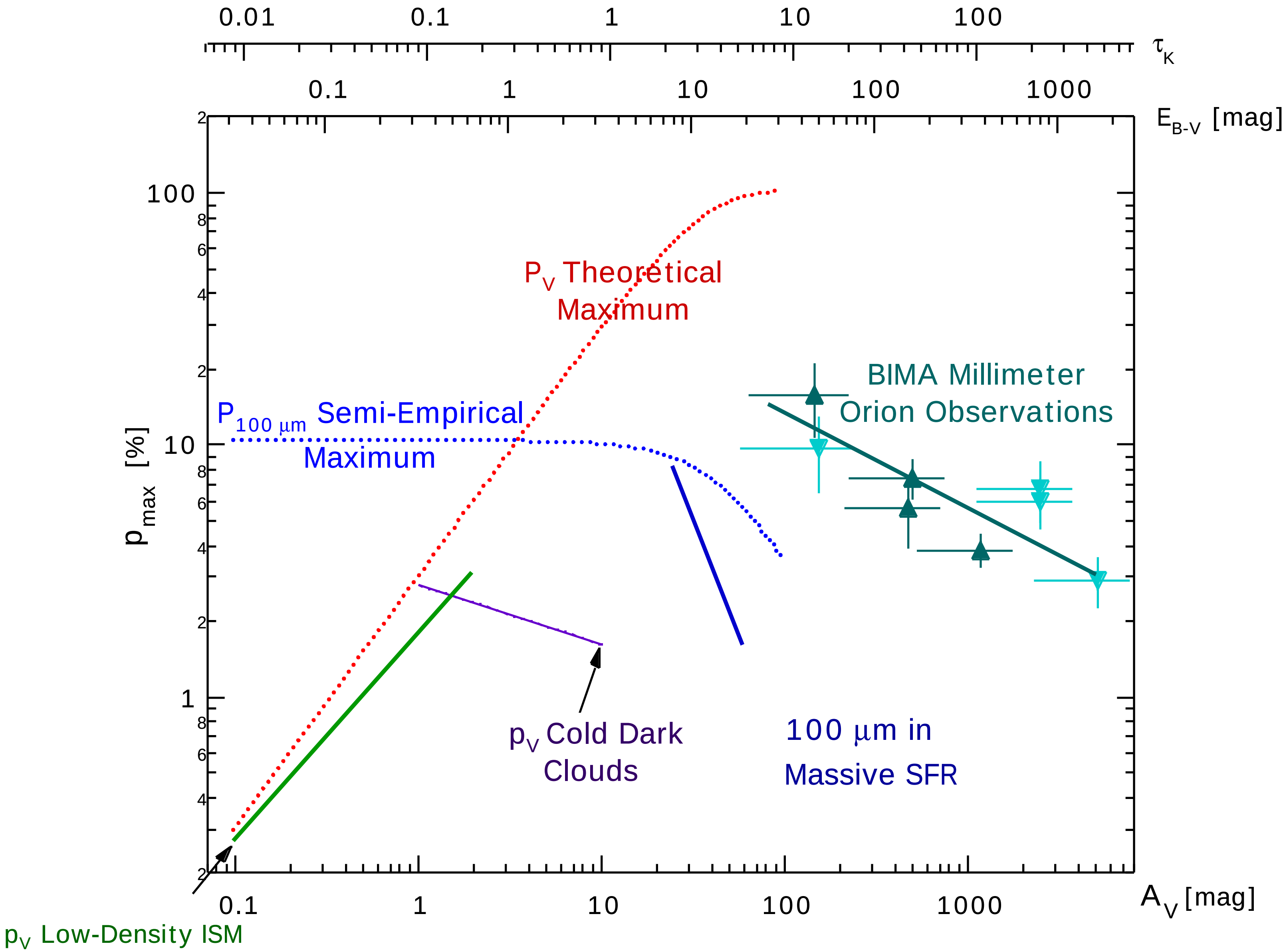
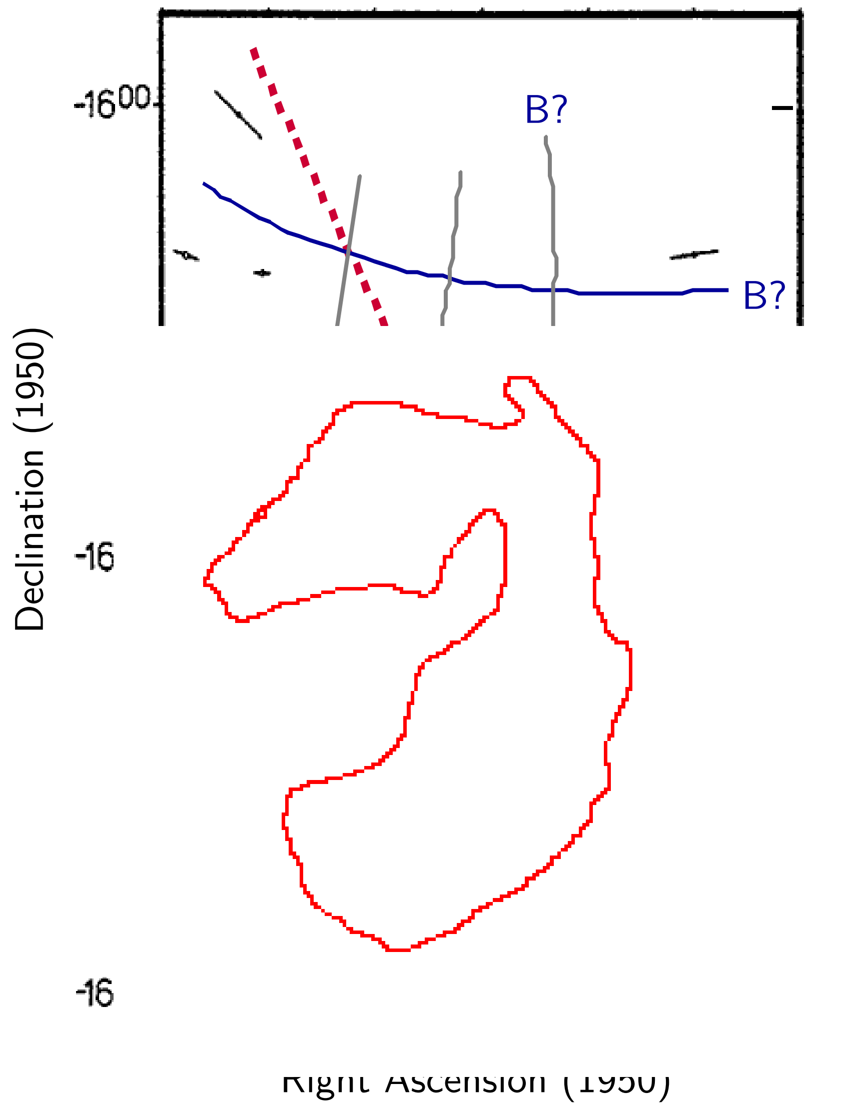


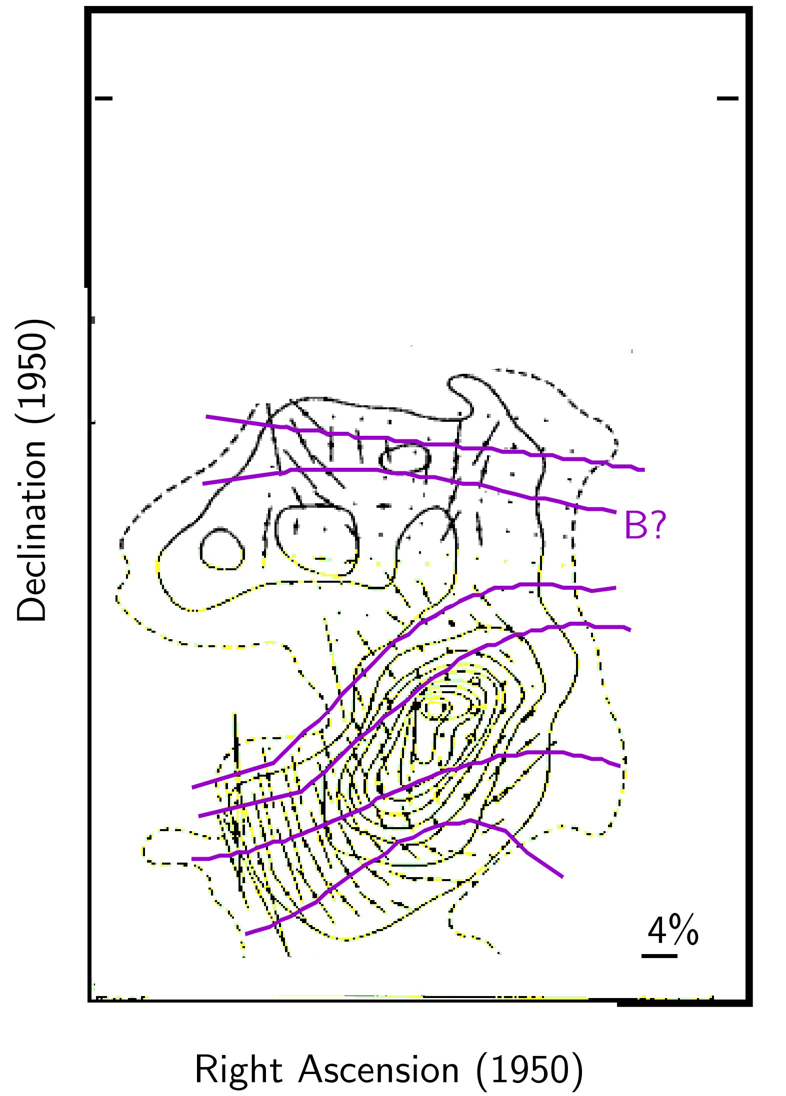
Figure from Goodman 1999.

What can we expect?

Polarization of Background Starlight in M17
(Schulz et al. 1981)

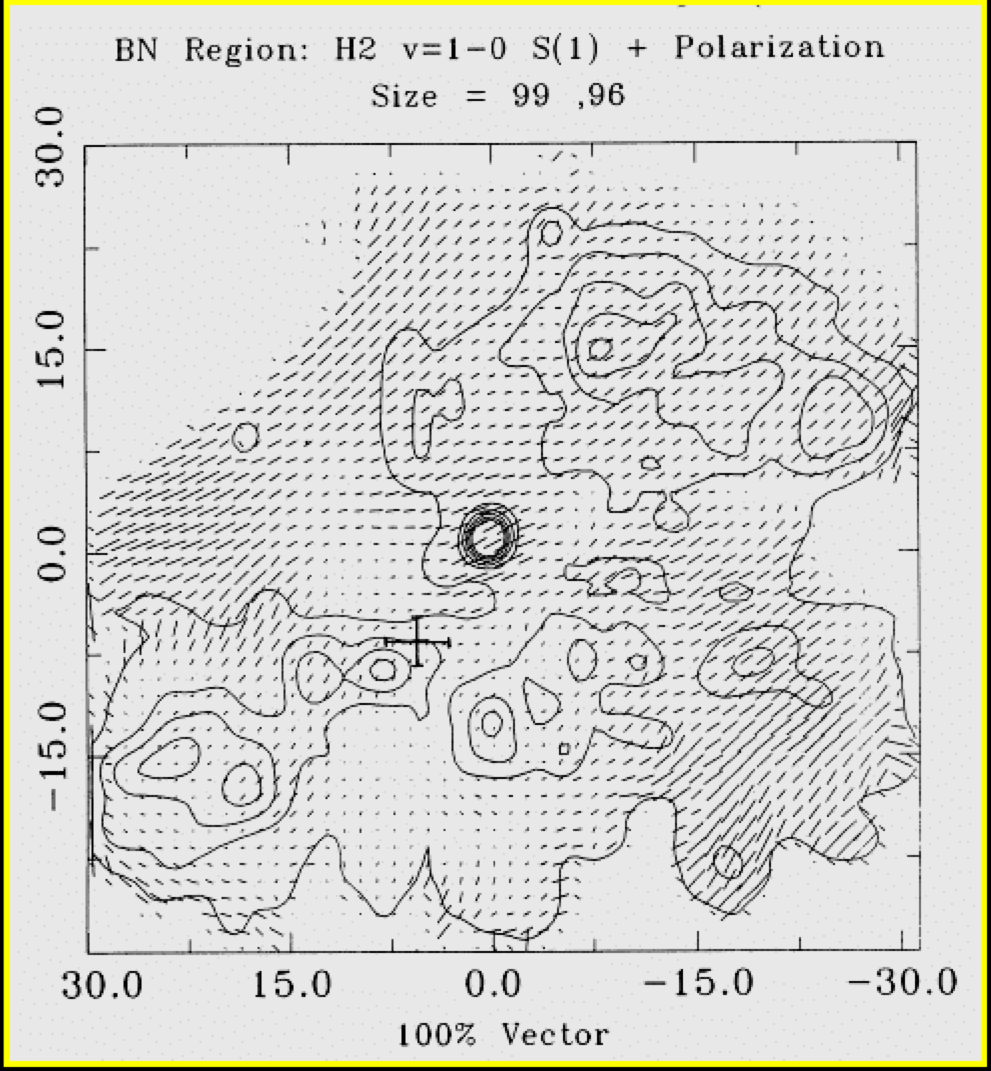


Polarization of 100 mm Dust Emission in M17
(Dotson 1994)



See Kristen, Goodman, Jones & Myers1999.

H_2 "Background" Polarimetry: Orion



Chrysostomou al. 1994

ISOPHOT Polarimetry - Science Results

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in collaboration with
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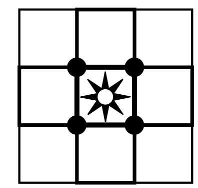
Jean Clavel (XMM SOC VILSPA)
Johan Lagerros (Astronomiska observatoriet Uppsala)
Richard Tuffs (MPIK HD)
Dan Clemens (Boston University)

21 October 1999

ISOPHOT Polarization Observational Modes

- **linear polarization with 3 polarizers at 0°, 120° & 240° (S/C y-axis frame)**
- **25 μm MIR aperture polarimetry (P2 detector, AOT P50)**
  - **79 arcsec aperture,**
  - **mode: single pointing (on – off)**
- **170 μm FIR array polarimetry (C200 detector, AOT P51)**
  - **2x2 detector pixels, 89.4 arcsec pixel size**
  - **mode: 2x2 raster with 1 pixel step $\rightarrow$ 3x3 pixel map**



- **Verification of measurement reproducibility:**
  $\geq$ 2 cycles: 0° – 120° – 240° – 0° – 120° – 240° ...
- **Consistency check:**
  polarization value of central C200 map position verified by all 4 pixels.
- **Removal of long term P2 detector drifts:**
  additional 0° measurement at end of polarizer sequence:
  0° – 120° – 240° – 0° ... 240° – 0°

Performance of ISOPHOT Polarization Modes for Point Sources

- **Most important parameters for final polarization accuracy:**
  - **Signal reproducibility in different cycles ⇔ robustness against drifts**
  - **Source-to-background contrast**
- **Examples for achieved polarization accuracies of point sources:**

detector	target	source flux [Jy]	pol. deg. [%]	source/ backg	S/N source	1 σ pol. error per cycle [%]
P2, P_25 (79")	NGC 7538	400	~ 3	17	150	0.8
	6 Hebe	~ 30	< 2	6.3	120	0.8
	9 Metis	~ 20	< 2	2	130	0.7
	Crab	~ 7	8	0.7	60	1.7
C200, C_160	Crab	~ 15	8	1.4	150	1.4
	3C 279	2.5	6	1.5 – 2	70 – 80	1.6
	3C 279	2.5	6	0.4	10 – 20	7
	3C 279	2.5	22	0.25	20 – 30	5
	3C 279	2.5	6	0.25	10 – 15	10
	α Boo	2.6	0	0.025	2	60

Note: Source/background ratios < 1 for C200 measurements: source not centered on pixel.

ISOPHOT Polarimetry Programmes

object type	target names	pol. mechanism	wavelength [μm]
Solar System Objects	6 Hebe, 9 Metis	(3)	25
Outflow Sources	NGC 7538, L 1551, HH 100	(2)	25
	NGC 1333, L 483, L 1157, IRAS0382, L 1448, L 1527, L 1544, L 1551	(2)	170
Molecular Clouds	TMC2, B213	(2)	170
Dark Clouds	GF9	(2)	170
Reflection Nebulae	NGC 7023	(2)	170
Supernova Remnants	Crab	(1) , (2)	25 , 170
Galaxies	NGC 1808, NGC 6946	(2)	170
AGNs	3C 279, BL Lac*	(1)	170

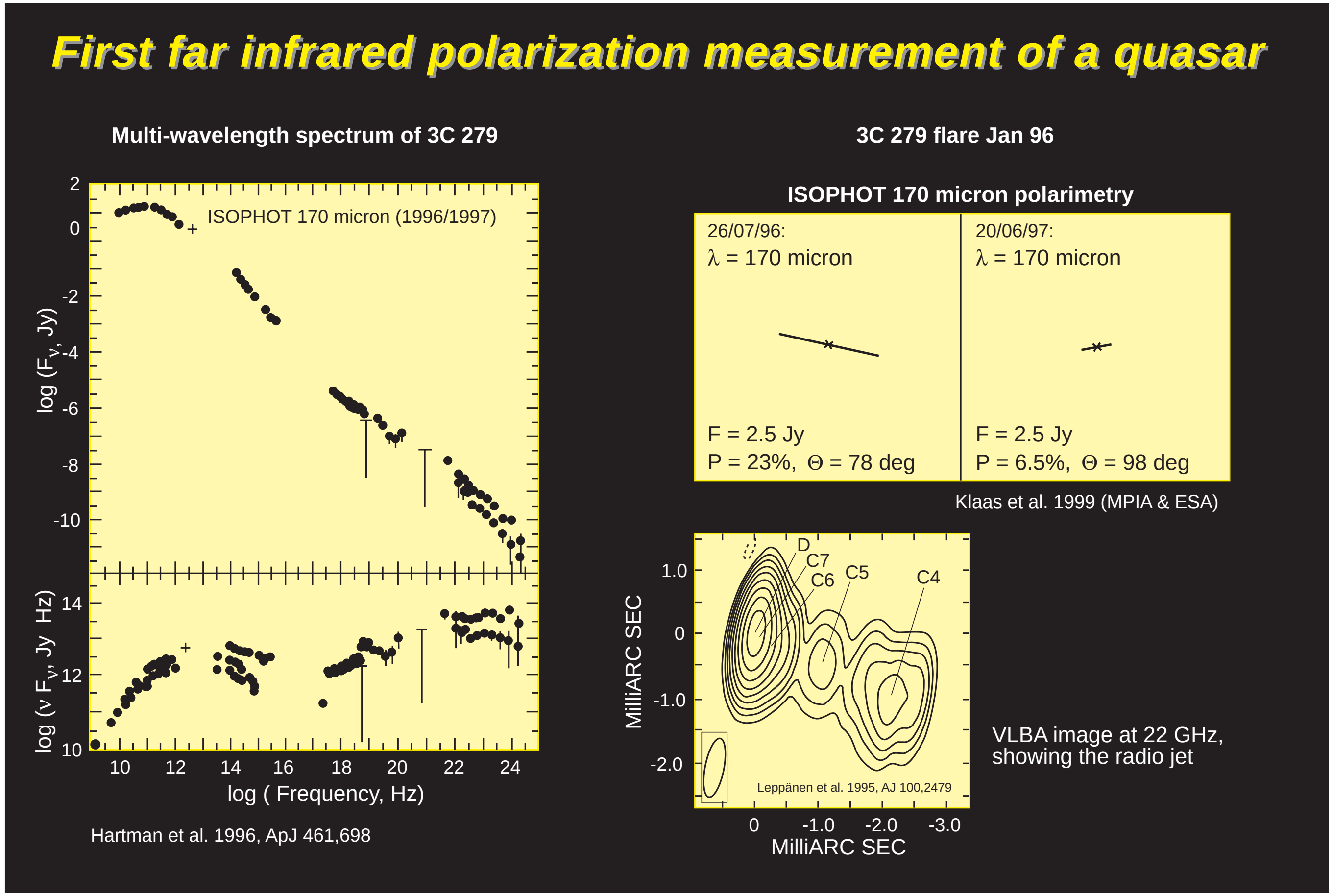
* source not detected due to cirrus confusion.

IR Polarization Mechanisms:

1) synchrotron emission
2) emission by elongated grains aligned by magnetic fields
3) scattering (by electrons, atoms, molecules, dust grains, reflection & refraction at boundaries between two media)

FIR polarization measurements of 3C 279

- **General Properties of 3C 279**
  - **OVV quasar (z = 0.538); t_{var} = few weeks to $\sim$ 6 months;**
    $\triangle$I: $\sim$ factor 20 in GeV range; $\sim$ factor 5 – 10 in IR-optical-UV range
  - **Flat spectrum radio quasar: relativistic jet pointing close to line-of-sight dominates emission**
- **Simultaneous multi-wavelength measurements from radio to γ-rays: two broad maxima in FIR and at GeV energies:**
  - **IR-optical-UV: optically thin synchrotron emission**
  - **Low frequency synchrotron self-absorption $\rightarrow$ flat radio spectrum**
  - **X-rays & γ-rays: inverse Compton (IC) up-scattering of ambient "seed" photons:**
    - **synchrotron photons themselves: synchrotron self-Compton (SSC) model**
    - **thermal photons from e.g. accretion disc: external Compton (EC) model**
- **SSC model favoured for interpretation**


First far infrared polarization measurement of a quasar
Multi-wavelength spectrum of 3C 279
ISOPHOT 170 micron (1996/1997)
log (Fν, Jy)
log (ν Fν, Jy Hz)
log (Frequency, Hz)
Hartman et al. 1996, ApJ 461,698
3C 279 flare Jan 96
ISOPHOT 170 micron polarimetry
26/07/96:
λ = 170 micron
F = 2.5 Jy
P = 23%, Θ = 78 deg
20/06/97:
λ = 170 micron
F = 2.5 Jy
P = 6.5%, Θ = 98 deg
Klaas et al. 1999 (MPIA & ESA)
D
C7
C6
C5
C4
MilliARC SEC
MilliARC SEC
Leppänen et al. 1995, AJ 100,2479
VLBA image at 22 GHz, showing the radio jet

Interpretation of 3C 279 FIR polarization

- **3C 279 showed γ-ray flare in Jan. 1996 (IAU Circ. 6294)**
- **First FIR polarization measurements of a quasar at two epochs:**
  - **1996-07-26: 22.8 $\pm$ 1.6 %, 77.9 $\pm$ 3.0 deg**
  - **1997-06-20: 6.5 $\pm$ 1.5 %, 98.0 $\pm$ 5.6 deg**
  - **Equality of total 170 μm flux: 2.5 Jy at both epochs**
  - **Polarization of first epoch roughly aligned with mas radio jet $\rightarrow \vec{\mathrm{B}} \perp$ base of jet; $P_{\mathrm{FIR}} \perp P_{\mathrm{radio}}$; $P_{\mathrm{FIR}} \parallel P_{\mathrm{opt/submm}}$**
- **High polarization degree at first epoch $\rightarrow$ Optically thin synchrotron emission (also at second epoch more likely optically thin emission; Pacholczyk 1970)**
- **Polarization varies drastically within one year $\rightarrow$ FIR emission area very compact $\rightarrow$ origin in core, but radio emission from outer knots**

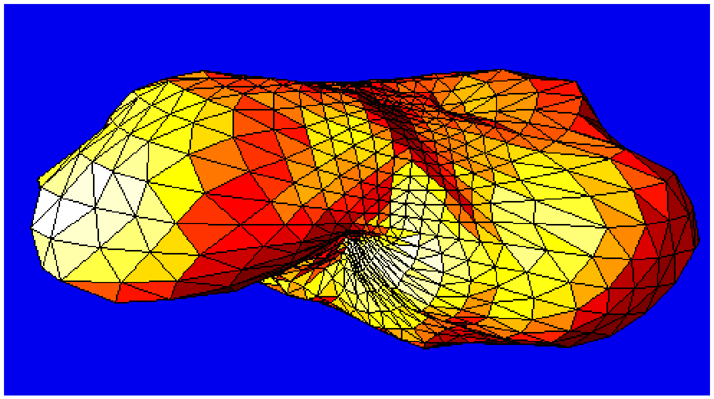
Interpretation of 3C 279 FIR Polarization Variability

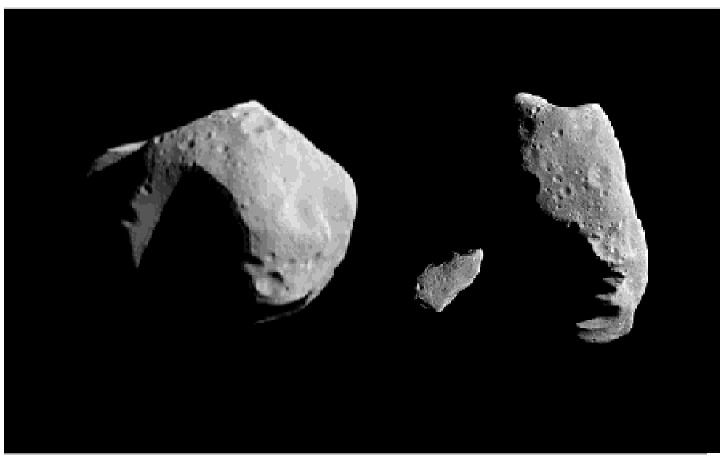
- **Correlation of polarization degree with flux at 1.1 mm (Nartallo et al., MNRAS 297, 667): $\rightarrow$ plane shocks enhancing flux and perpendicular magnetic field?**
- **ISOPHOT photometry: FIR flux equal for high and low polarization stage! (flux not constant all the time, but went through minimum in Dec. 1998, Haas et al., ApJ 503, L109)**
- **Orientation of radio polarization flips between the stationary knots (Leppänen et al., AJ 110, 2479)**
- **Explanation by geometry effects:**
  - **New knot formed in core region (γ-ray flare!), emitting bulk of FIR highly ordered field $\perp$ to jet axis $\rightarrow$ high polarization degree**
  - **When travelling out re-orientation (bents) and disordering of magnetic field polarization angle less well aligned with jet axis**
- **Constraints on jet models**

MIR Polarimetry of Asteroids

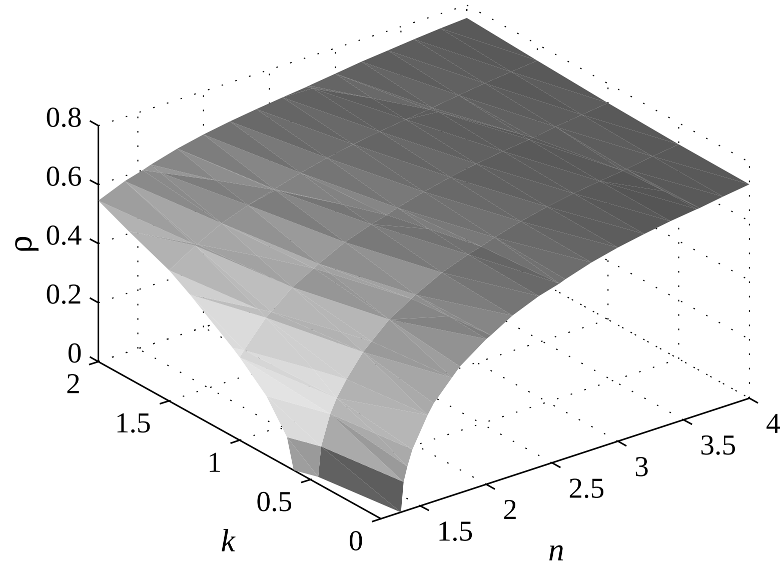
- **Observational results: 25 μm polarimetry of 6 Hebe, 9 Metis:**
  P = $\sim$ 0.5 %, σ_{P} = 0.8 % $\leftrightarrow$ no polarization
- **Thermophysical model extended to predict amount of polarized thermal emission**
  - **Scattering processes in the visual and IR across rough surface**
    $\rightarrow$ lateral T variations $\rightarrow$ magnitude and state of polarized thermal emission
  - **Absolute model fluxes in good agreement with photometric results**
  - **Upper limits of polarization $\rightarrow$ constraints on surface properties**
    - **Metis: low refractive index and high surface roughness**
    - **Hebe: inconclusive, since observed at minimum of polarization curve**
  - **Polarimetry provides improved input parameters for thermophysical modelling**

Polarimetry of Asteroids





Mathilde Gaspra Ida



lower left: shapes of asteroids

upper left: 3D temperature model of 243 Ida

right: constraints on surface roughness ρ and refractive index $|m| = |n+ik|$ for 9 Metis from MIR polarization measurements: the region below the sheet is excluded

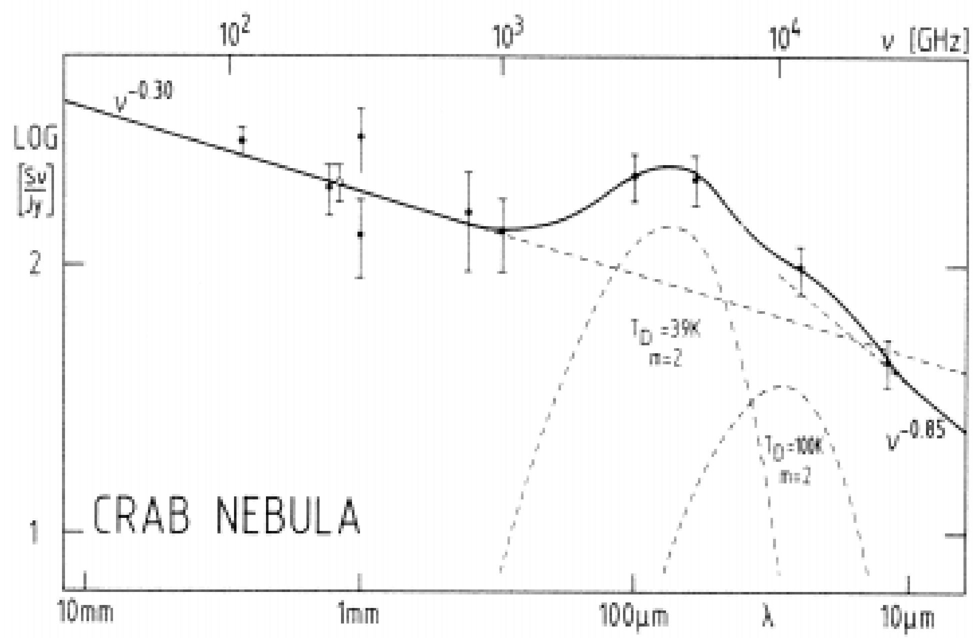
MIR & FIR polarimetry of the Crab nebula

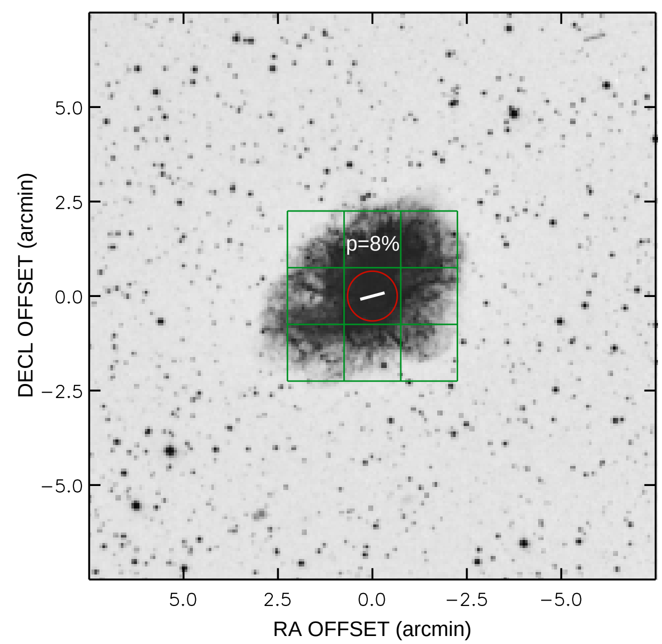
- λ 10 mm to 10 μm SED: superposition of "FIR bump" on synchrotron power laws (Mezger et al., A&A 167, 145)
- synchrotron break in λ 10 μm to 28 μm range
- Nature of "FIR bump"?
  - dust or line emission from supernova ejecta in filaments
  - synchrotron component (predicted by diffusion loss models for sources with flat injection spectrum)
- If synchrotron: polarization properties should be similar to those found at cm & mm wavelengths $\leftrightarrow$ further constraints for location of synchrotron break
- Pointing on position of the peak polarized intensity predicted from λ 9 mm 100 m Effelsberg telescope maps
- Aperture and central pixel of FIR polarization map include pulsar

MIR & FIR polarimetry of the Crab nebula

- **25 μm polarization: P = 7.7 % ± 1.6 % Θ = 105°± 5°**
- **170 μm polarization: P = 8.2 % ± 1.4 % Θ = 103°± 5°**
  for central map pixel, derived for all 4 C200 pixels! → constant polarization over larger area or dominating point source
- **No agreement with extrapolations from mm-measurements (P = ∼ 20 %, Θ = 45°) → thermal nature of FIR bump most likely**
- **Comparison with optical polarization measurements:**
  - **High resolution optical polarization maps by McLean et al., Nature 304, 243: P and Θ_P are the same as for the pulsar in the optical!**
    (P = 15 % and $\Theta_P \sim 140°$ for nebula)
  - **Time resolved polarization of Crab pulsar by Smith et al., MNRAS 233, 305: FIR polarization degree and angle correspond best to optical polarization values of pulse and inter pulse period**
- **On-going analysis by Klaas, Laureijs, Müller & Tuffs**

MIR & FIR Polarimetry of the Crab Nebula

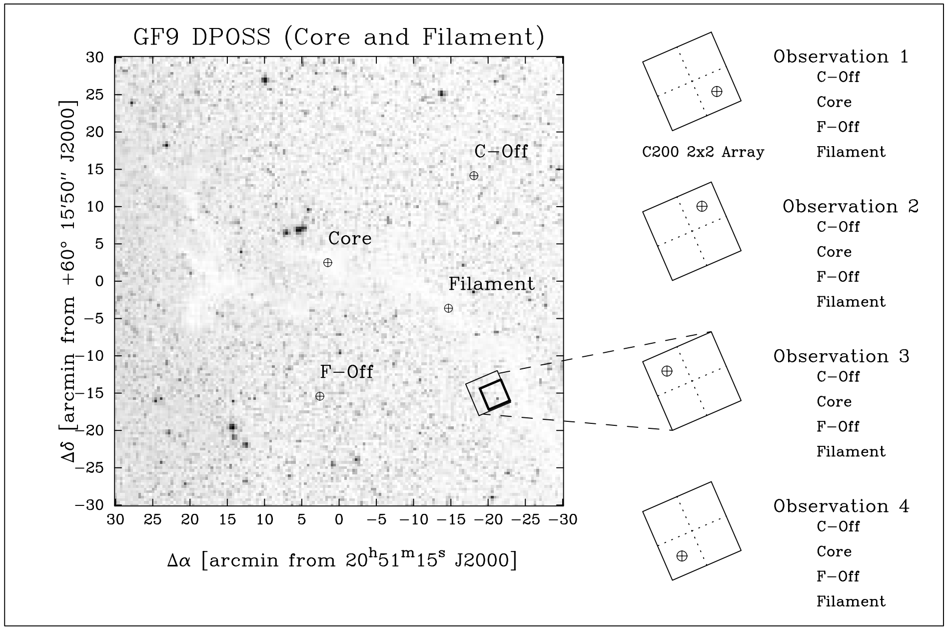




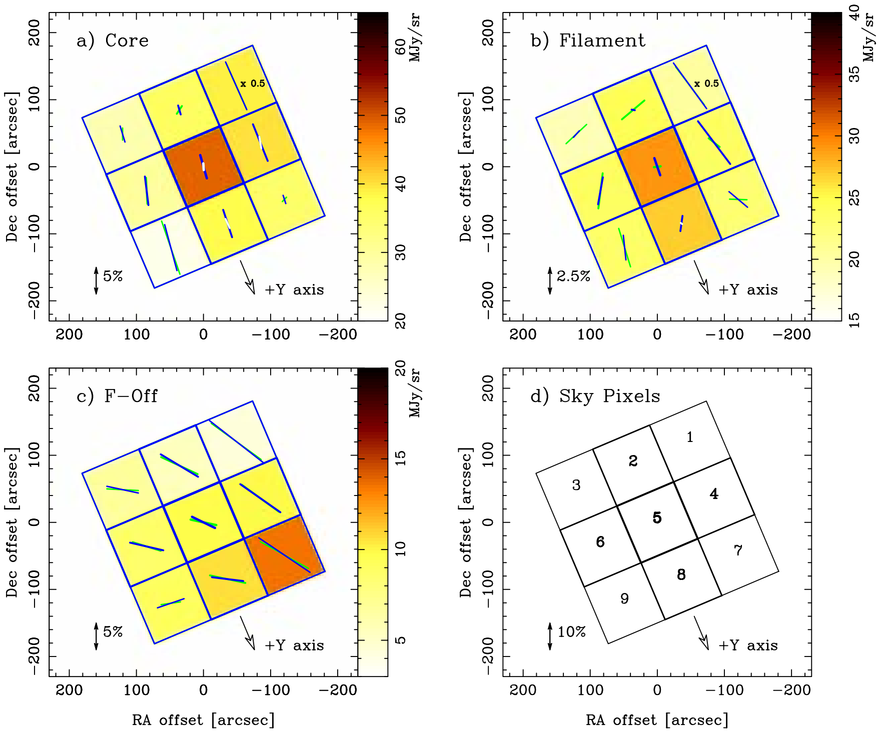
Magnetic Fields in the Dark Cloud GF9

- **Observations & analysis by D.P. Clemens, K.E. Kraemer & D.R. Ciardi**
- **170 μm polarization maps of GF9 core & filament + 2 reference positions**
- **5 % polarized dust emission detected from core, filament & 1 reference position magnetic fields within dark clouds directly detected**
- **Polarization properties of core and filament different:**
  - **dense core with Class 0 source: parallel polarization vectors $\rightarrow$ highly uniform embedded magnetic field**
  - **non-star forming filament: disordered magnetic field $\rightarrow$ magnetic turbulence $\leftrightarrow$ support against collapse?**

Magnetic Fields in the Dark Cloud GF9



courtesy of D. Clemens (Boston University)



Summary

- **ISOPHOT IR space polarimetry contributes to a variety of astrophysical issues:**
  - **First FIR polarization measurements of a quasar**
    → constraints on jet models
  - **MIR polarization measurements of asteroids**
    → constraints of surface properties & improve thermophysical modelling
    → well described standard sources
  - **FIR polarization measurements of Crab nebula:**
    → more clues on nature of Crab SED, magnetic field structure around central engine
  - **FIR polarization measurements of dark clouds**
    → magnetic fields structures, role of magnetic fields in star forming process

Lessons Learnt from ISOPHOT Space Polarimetry

- **FIR detector, filter & polarizer technologies permit sensitive polarimetry**
- **Performance of polarimetry of point sources:**
  $\sigma_{\mathrm{P}} = 1\,\%$ for sources of a few Jy in $\sim$ 1/2 hour
- **Amount of measurement time needed mainly determined by stabilization of high ohmic Ge:Ga detectors**
  - **due to glitches by ionizing radiation**
  - **due to signal transients after flux changes**
- **Sensitivity limit determined by source-to-background contrast and in some areas by cirrus confusion**
- **Partly open issues in ISOPHOT polarimetry**
  - **Refinement of instrumental polarization numbers**
  - **Better understanding of beam effects for extended sources**

Publications on ISOPHOT Polarimetry

1) Laureijs, R.J. & Klaas, U., 1997: "ISOPHOT Polarization AOTs PHT50 and PHT51", ISO Observatory Document, 12-Dec-1997 (http://www.iso.vilspa.esa.es/users/expl_lib/PHT/pol_rel.html)

2) Klaas, U., Müller, T.G., Laureijs, R.J., et al., 1999: "Polarization Measurements with ISOPHOT: Performance and First Results", ESA Conference Proceedings SP-427, "The Universe as seen by ISO", P. Cox & M. Kessler (eds.), ESTEC Noordwijk, p. 77

3) Klaas, U., Laureijs, R.J., Müller, T.G., Kreysa, E., Krätschmer, W., 1999: "Data Reduction, Calibration and Performance of the ISOPHOT Polarization Modes", Proceedings of the VILSPA Polarization Workshop, May 25-28, 1999 (http://www.iso.vilspa.esa.es/meetings/polarisation/paper/web/)

4) Klaas, U., Laureijs, R.J., and Clavel, J., 1999: "Far-infrared Polarization of the Quasar 3C 279", ApJ 512, 157

5) Klaas, U., Laureijs, R.J., and Clavel, J., 1999: "FIR Polarization of the Quasar 3C 279", Proceedings of the VILSPA Polarization Workshop, May 25-28, 1999 (http://www.iso.vilspa.esa.es/meetings/polarisation/paper/web/)

6) Lagerros, J.S.V., Müller, T.G., Klaas, U., and Erikson, A., 1999: "ISOPHOT Polarization Measurements of the Asteroids 6 Hebe and 9 Metis", accepted for publication in Icarus

7) Clemens, D.P., Kraemer, K.E., and Ciardi, D.R., 1999: "First Detection of Magnetic Fields in a Dark Cloud from Space: ISO Far-Infrared Polarimetry Observations of GF9", ApJ submitted

SCUBA Polarization results: 1998-1999

Jane Greaves,

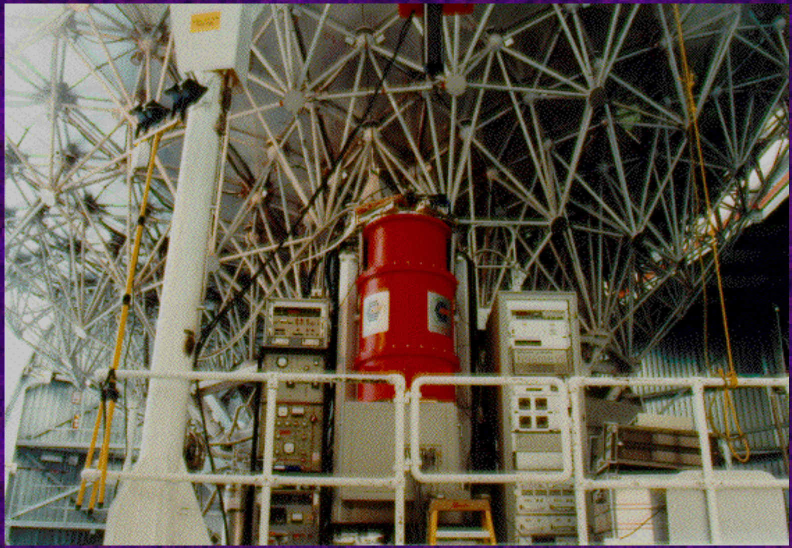
Joint Astronomy Centre,

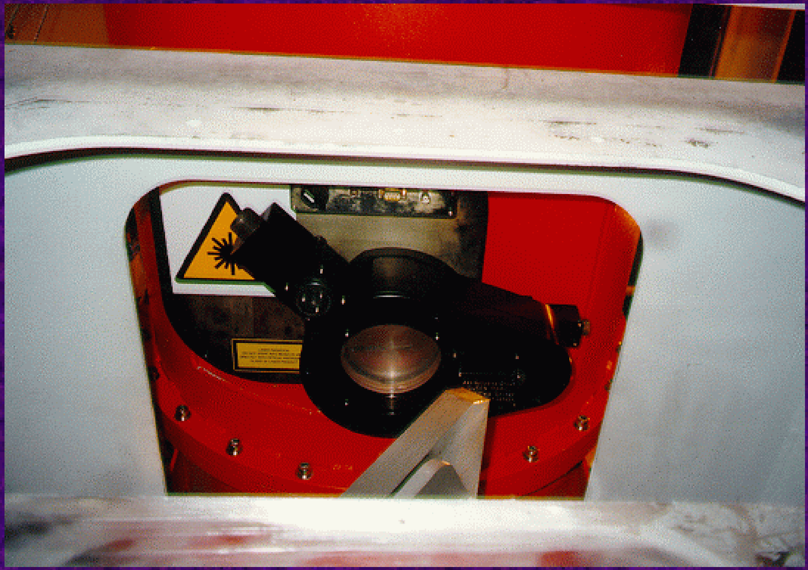
Hawaii

with special thanks to:
Wayne Holland, Tim Jenness,
David Berry and Antonio
Chrysostomou

SCUBA Polarimeter at the JCMT

The Submillimetre Common-User Bolometer Array (SCUBA) is a background limited 350-850 μm camera with a 2.3 arcmin FOV on the 15m James Clerk Maxwell Telescope in Hawaii



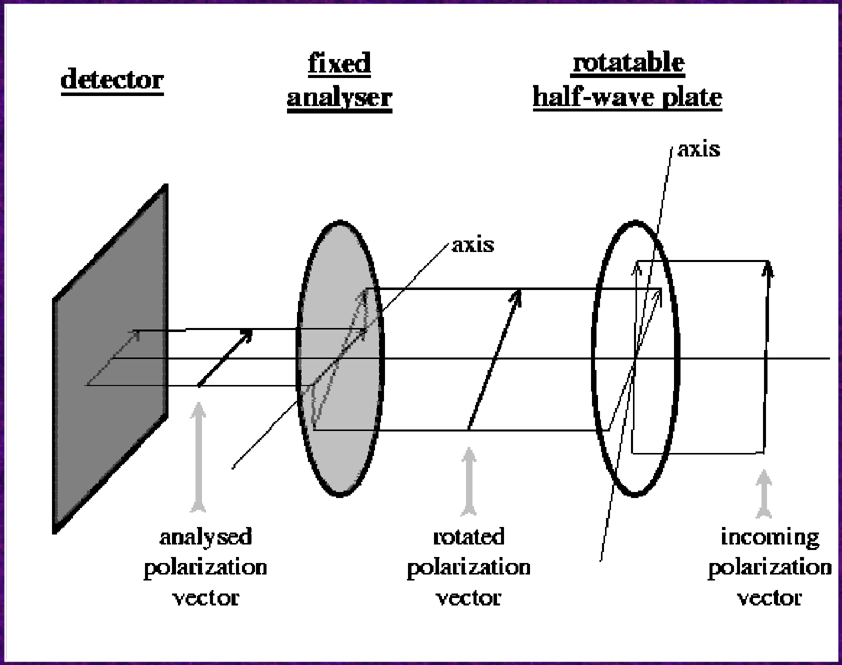


The Polarimeter, which is mounted externally over the cryostat window, is an achromatic multi-half-wave plate design, built in the UK at Queen Mary & Westfield College.

- **http://www.jach.hawaii.edu/JACpublic/JCMT/scuba/scupol**

Polarimeter design

The polarimeter wave-plates are of the Pancharatnam design (an odd number of $\lambda/2$ plates whose fast axis orientations differ by 60 degrees). This gives excellent achromatic performance (> 95% polarization modulation efficiency) with some loss of transmission (≤10%). We obtain simultaneous images at 850 and 450 μm, (or at 750 and 350 μm using a different filter set), plus have 1.3/2 mm single pixels.



- Incoming radiation passes through the rotating waveplate and then a fixed 'analyser' (etched wire grid)
- Thus SCUBA effectively sees a component of a rotating source plane of polarization
- We analyse these modulated images as a function of 16 'step' angles of the waveplate around a circle.

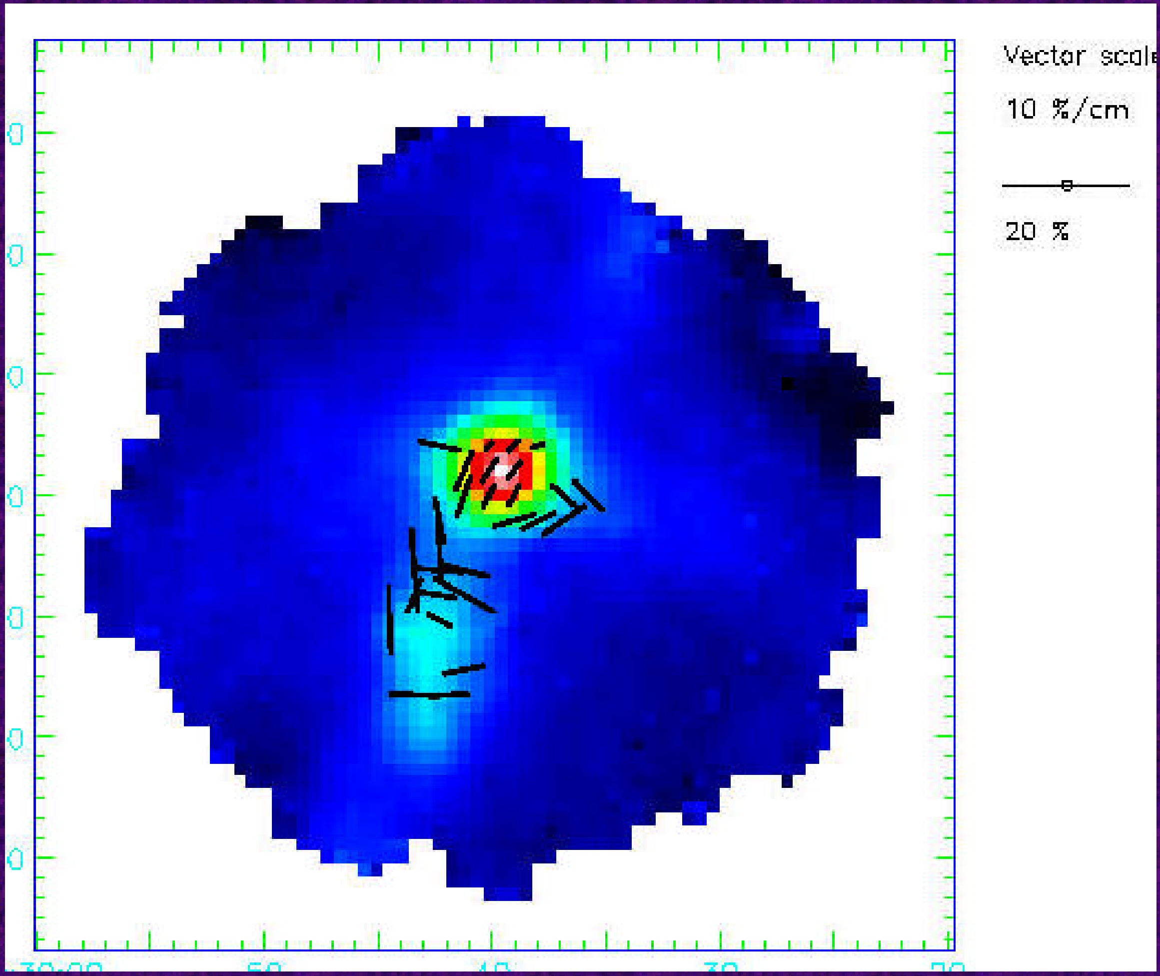
Polarimeter performance & use

- Performance is limited mainly by the SCUBA NEFD's (~ 90 mJy $Hz^{-1/2}$ at 850 μm, our primary wavelength) and we have detected polarized sources as faint as ~ 0.3 Jy.

- Polarimeter use by the general JCMT community is high (about 12% of all the current SCUBA applications) - so far 13 PI's have been awarded time (1998/1999).

- We've aimed to make the observing 'normal astronomer-friendly' - the data can be reduced completely automatically at the telescope.

A typical project - protostars...



L1157 core and outflow:

ordered field points down the start of the flow but then is swept up sideways in the bright knot?

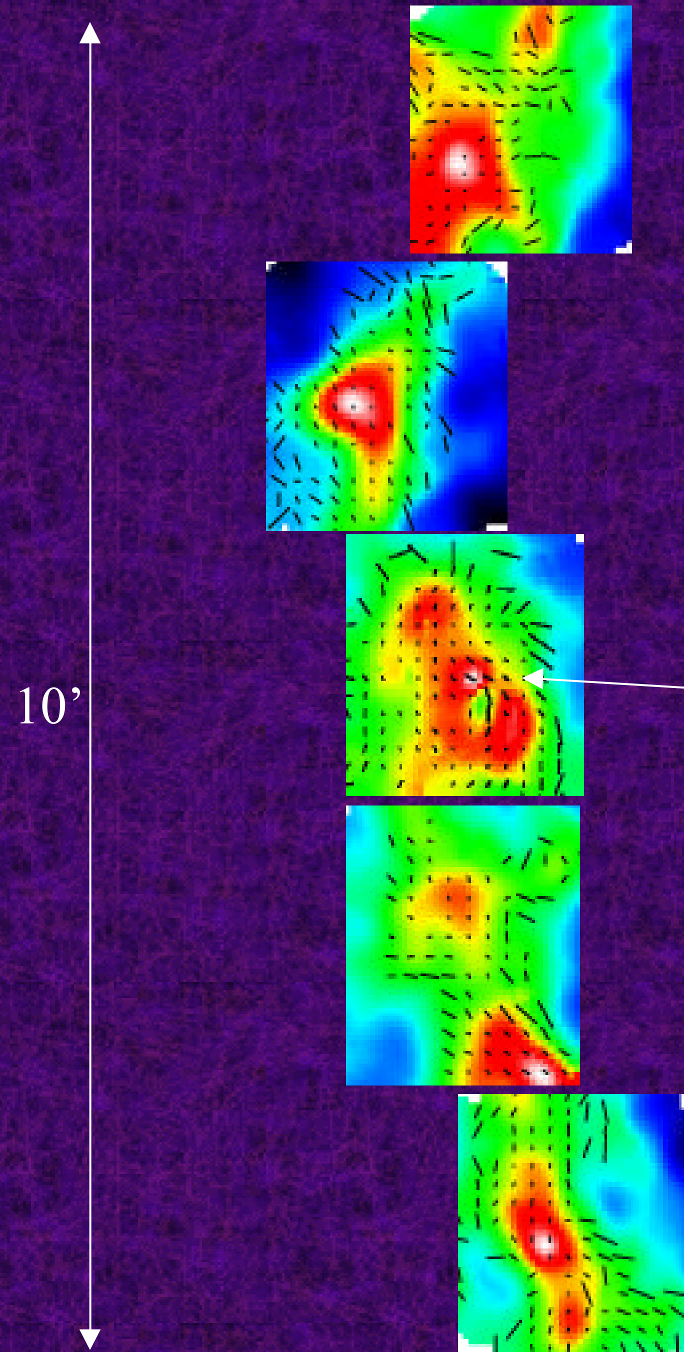
(integration was 1.5 hours, peak flux is ~ 1.4 Jy)

(in these figures: vector length ∝ pol-% and (mostly) rotated 90 deg. to show field)

Galactic Centre mosaic

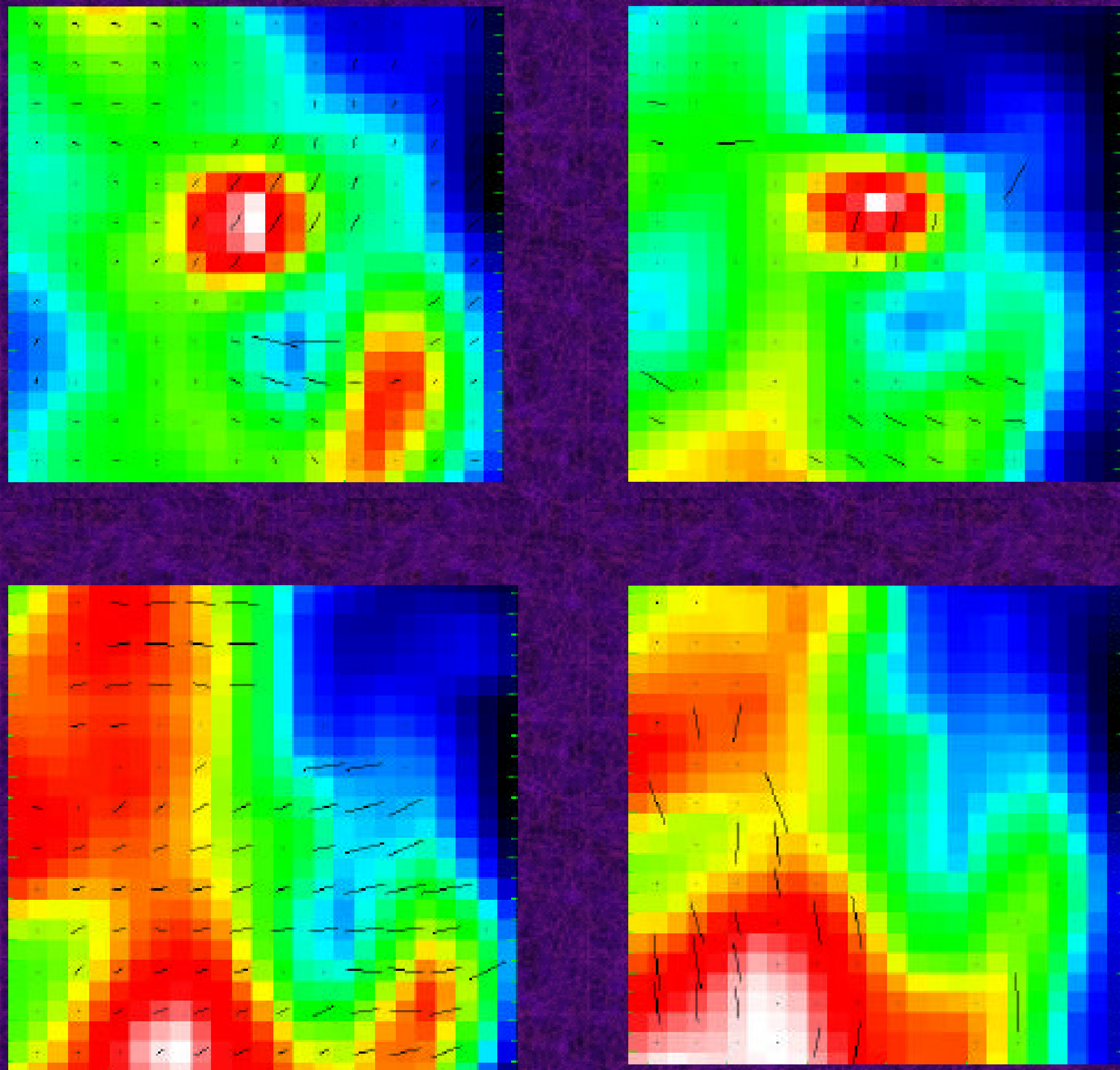
Note the wave-like field in the southern clouds.

Near Sgr A*, the field follows the ‘mini-spiral’ seen in ionized gas, inside the circum-nuclear ring.



Chrysostomou et al., in prep.

Galactic Centre: multi-λ



key:

850 750

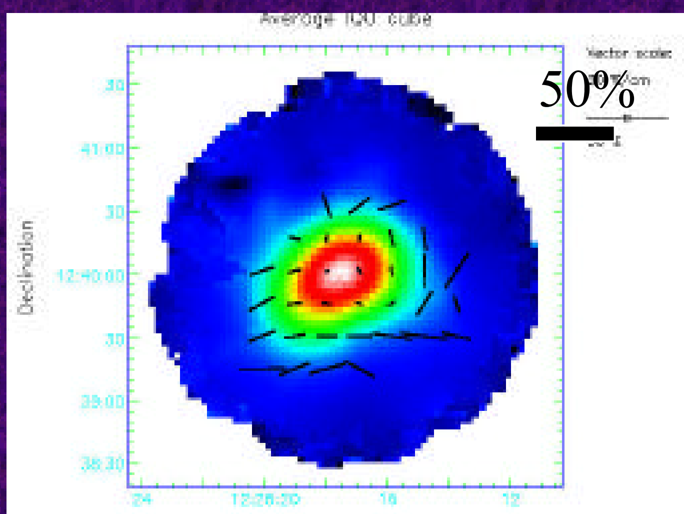
450 350

(last two have some problems with too small chop throws)

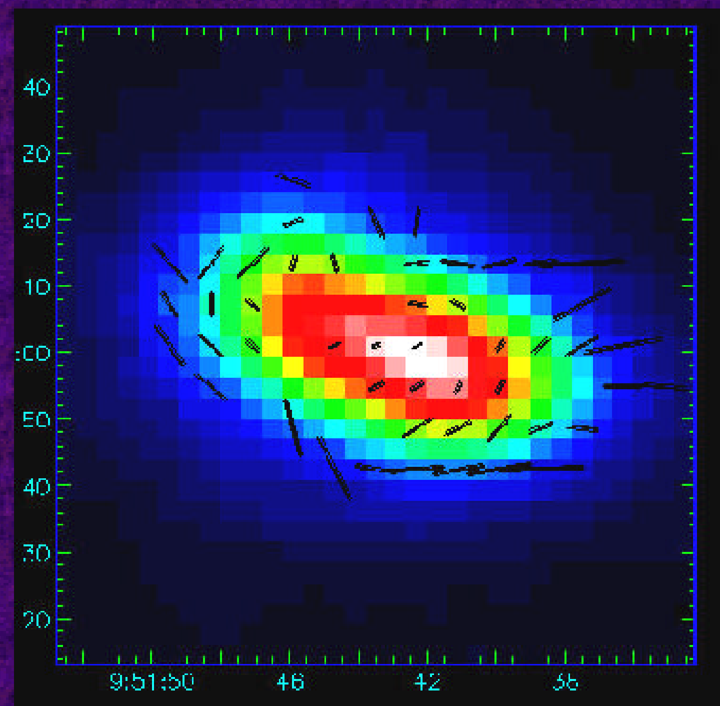
Extragalactic polarimetry

A key question for cosmologists is the polarization level of the cosmic microwave background radiation... but first you need to know the contamination from polarized foreground galaxies!

M82 is polarized at a level of about 1% to 3% - models by De Zotti et al. suggest that this will not be a problem for CMB polarimetry...



Leeuw et al., in prep.



but e.g.the the jet region in M87 is much more polarized!

The future - and M4

- **SCUBA-2** is planned for ~2004 on the JCMT & can use the same polarimeter as SCUBA. It will map ≥ 100x faster than SCUBA with a 8' FOV and dual 850/450 μm arrays...

- BUT:
  - it would still take ~ 1000 nights to extend our Galactic Centre mosaic to the M4 Galactic Plane survey region! (100x10 deg.)
  - 100 μm emission is much brighter then 850/450 μm (except for extremely cold dust), so typical clouds such as Elias16 would be much easier to do in the far-IR

Thus we can only do large-scale surveys with M4….

Wavelength Dependence of Far-IR and Submillimeter Polarization

C. Darren Dowell (Caltech)
21 October 1999

Data: Clouds forming massive stars
KAO 60 μm, 100 μm
CSO 350 μm
[JCMT 850 μm]
[NRAO 1300 μm]

Observations:

I) Cloud cores (flux maxima):
Often, $dP/d\lambda > 0$. (Optically thick ⇒ optically thin?)
In one unusual case, $dP/d\lambda << 0$. (abs. in Sgr B2)

II) Cloud envelopes (everywhere else):
A) $d\theta/d\lambda <> 0$ ⇒ Magnetic field structure + multiple cloud (temperature) components

B) $d\theta/d\lambda \approx 0$: Observe $dP/d\lambda < 0$ (λ=60-350 μm).
⇒ Multiple dust components
1) Emissivity index (β)/polarization correlation
2) Temperature/polarization correlation

References:

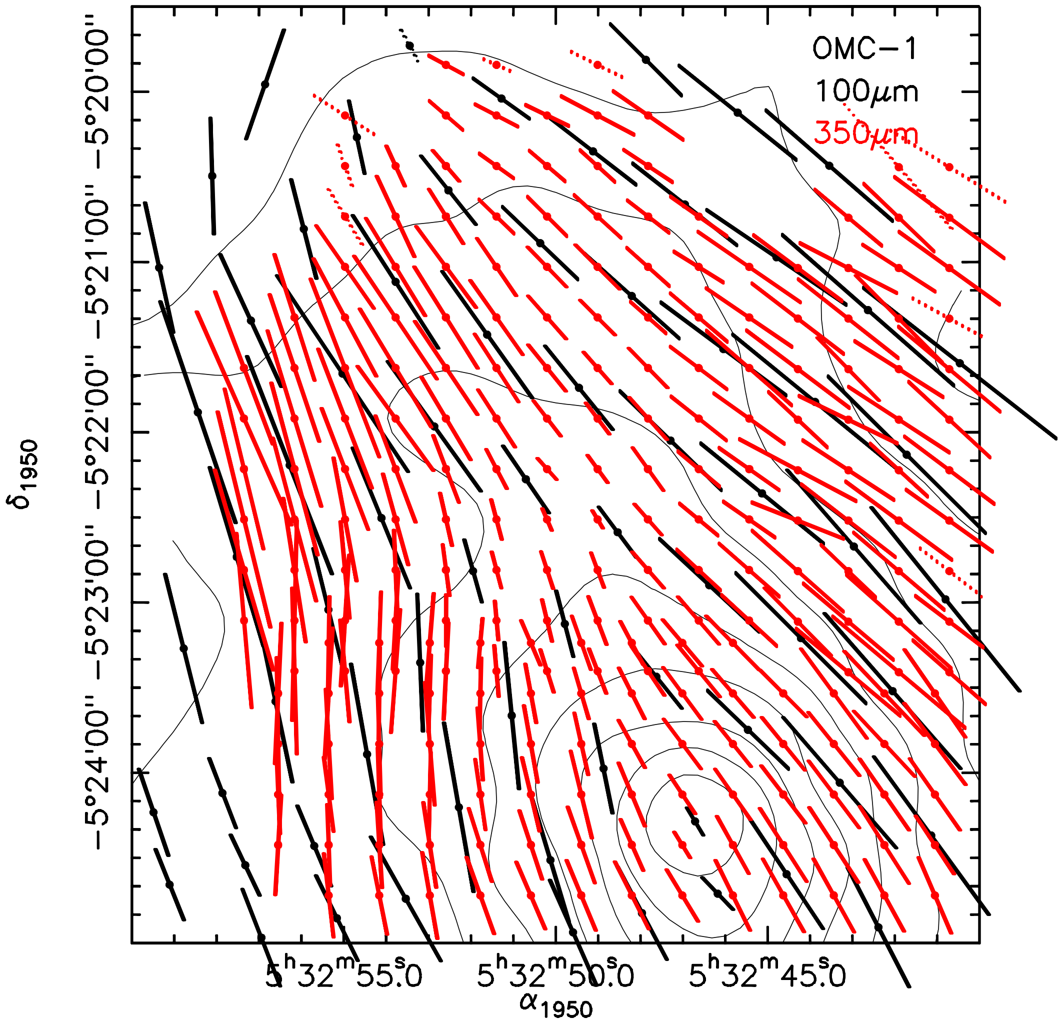
Hildebrand et al. (1999) – ApJ 516: 834 – $dP/d\lambda < 0$ in envelopes
Schleuning (1998) – ApJ 493: 811 – $dP/d\lambda > 0$ in Orion core
Dowell (1997) – ApJ 487: 237 – $dP/d\lambda << 0$ in Sgr B2 core

Polarization Histograms: KAO and CSO

(Figure to be pasted in.)

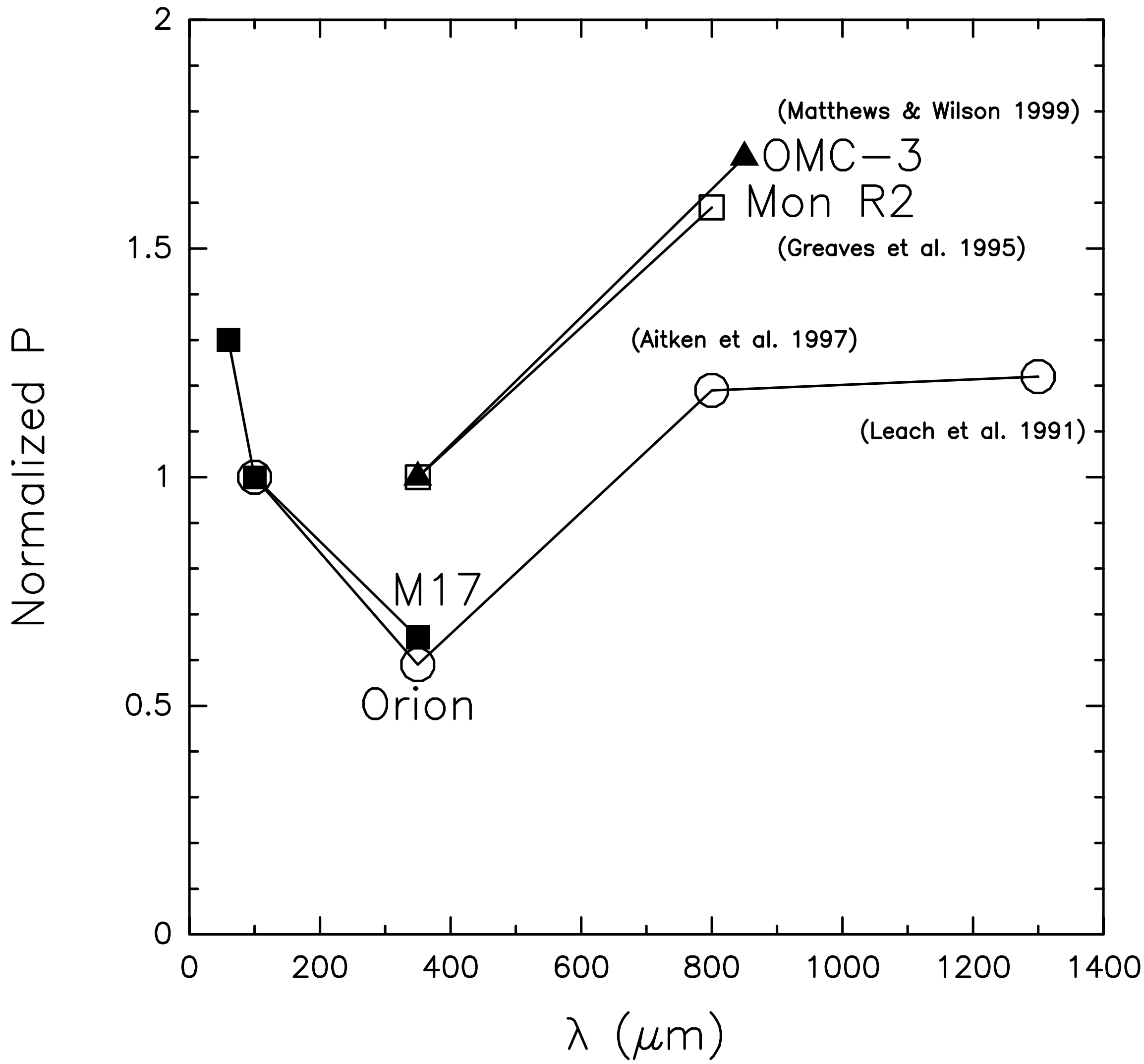
Note: Complete data sets with only partial overlap of sources. See Hildebrand et al. (1999).

Orion Envelope Polarimetry



P(350 μm)/P(100 μm) = 0.59.

FIR/Submm Polarization Spectrum



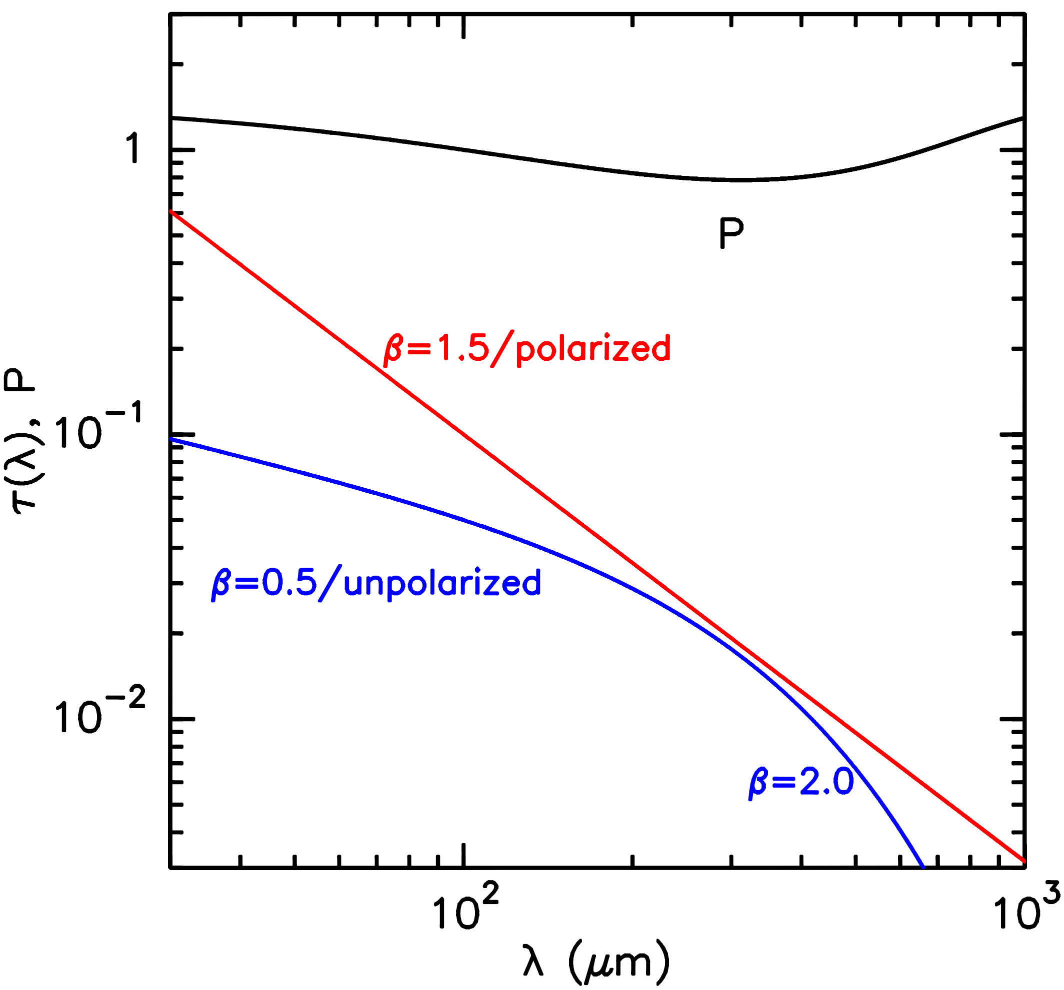
FIR Polarization Spectrum – Not the Signature of a Single Grain Species

(Figure to be pasted in.)

Oblate grains, a/b = 0.5. See Hildebrand et al. (1999).

Explanations for Dip in Polarization Spectrum

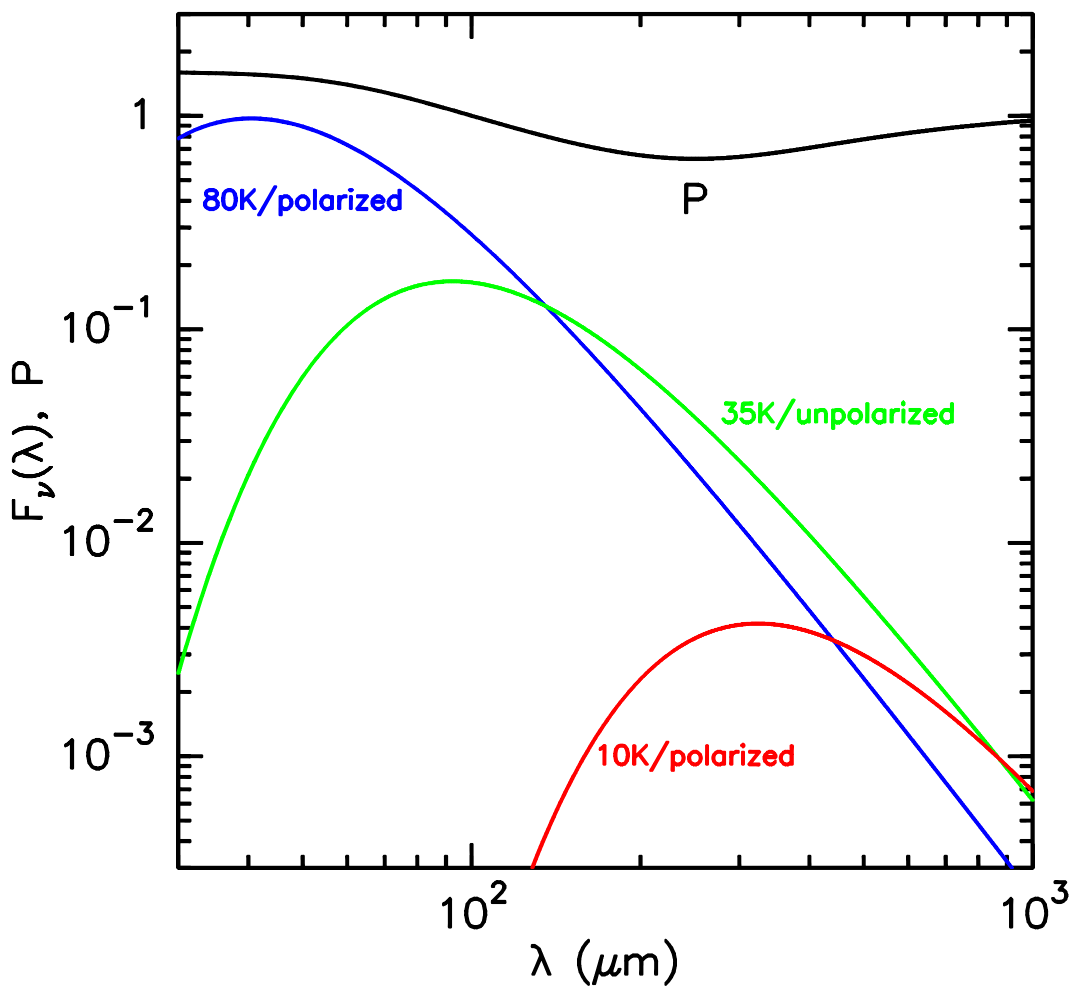
1) 2+ grain components, one polarized and one not, with different β's:



Silicate/graphite (1:1) with Draine(1985) emissivity can reproduce **neither** the steepness of the 60-350 μm polarization spectrum **nor** the rise toward 1 mm.

Explanations for Dip in Polarization Spectrum

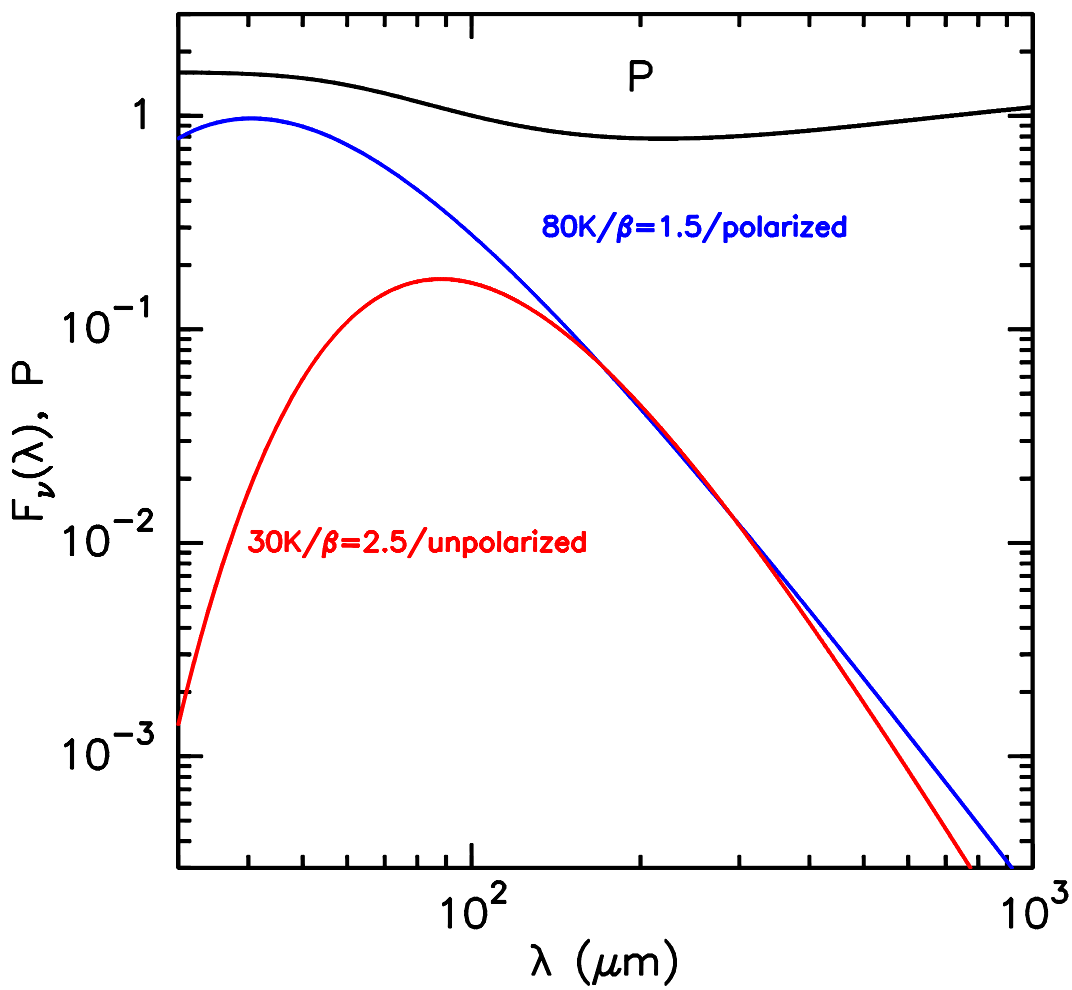
2a) 2+ temperature components, one polarized and one not:



80K, polarized regions – near embedded stars
35K, unpolarized regions – deep in cloud, away from stars. ‘Bad’ grains.
10K polarized regions – cloud surfaces (?) [Not in original Hildebrand et al. (1999) model.]

Explanations for Dip in Polarization Spectrum

2b) Combination of temperature and emissivity effects:



Evidence for anticorrelation of temperature and submillimeter β in Orion: Lis et al. (1998), ApJ 509: 299.

Predictions

Hildebrand et al. (1999) suggest that grains exposed to UV/optical photons are better aligned. Resulting predictions:

1) Warmer lines of sight should have larger polarization.

   [Existing data: In Orion, weak correlation of P(100 μm) with F_υ(100 μm)/F_υ(350 μm); stronger correlation for P(350 μm). Seeing mostly 'good' grains at λ<=100 μm in clouds with OB stars?]

2) Optically thick clouds devoid of stars should have relatively low polarization.

3) Translucent clouds should have relatively large submillimeter polarization. If the graphite grains are unaligned and are warmer than the aligned silicate grains, then the far-IR polarization will be smaller. ($dP/d\lambda > 0$.)

CMB Foreground from Aligned Dust

A. Lazarian
Univ. of Wisconsin, Madison

Goal of the research:

Disentangle CMB polarized emission from the polarized dust contribution

Science:

CMB: additional info on cosmological parameters, e.g. reionization optical depth, tensor to scalar amplitude ratio

IMPORTANCE: constrains inflationary models, provides model-independent test of the existence of primordial gravitational wave background

Magnetic fields: maps of magnetic fields including high and intermediate attitudes

IMPORTANCE: provides understanding of magnetic field origin and evolution

Physics of Dust: dust polarization as a function of wavelength

IMPORTANCE: contributes to the solution of the mystery of grain alignment; constrains grain-size distribution and interstellar conditions

Polarized Foreground from Dust

1. Rotational emission from spinning ultra-small grains ($a < 10^{-7}$ cm, $\nu < 70$ GHz).
2. Vibrational emission from classical large grains ($a > 10^{-6}$ cm, $\nu > 70$ GHz)

Reviews:

Lazarian, A., Goodman, A., & Myers, P. 1997, *ApJ*, **490**, pgs 273

Draine, B.T., & Lazarian, A. 1999, astro-ph 9902356

Prunet, S., & Lazarian, A. 1999, astro-ph 9902314

Approach to foregrounds

To separate the contribution at the frequency range of interest for CMB one can measure the polarized signal at higher frequencies at which the contribution is dominated by dust. Then one can subtract the emission provided that we know how polarized emissivity scales with frequency.

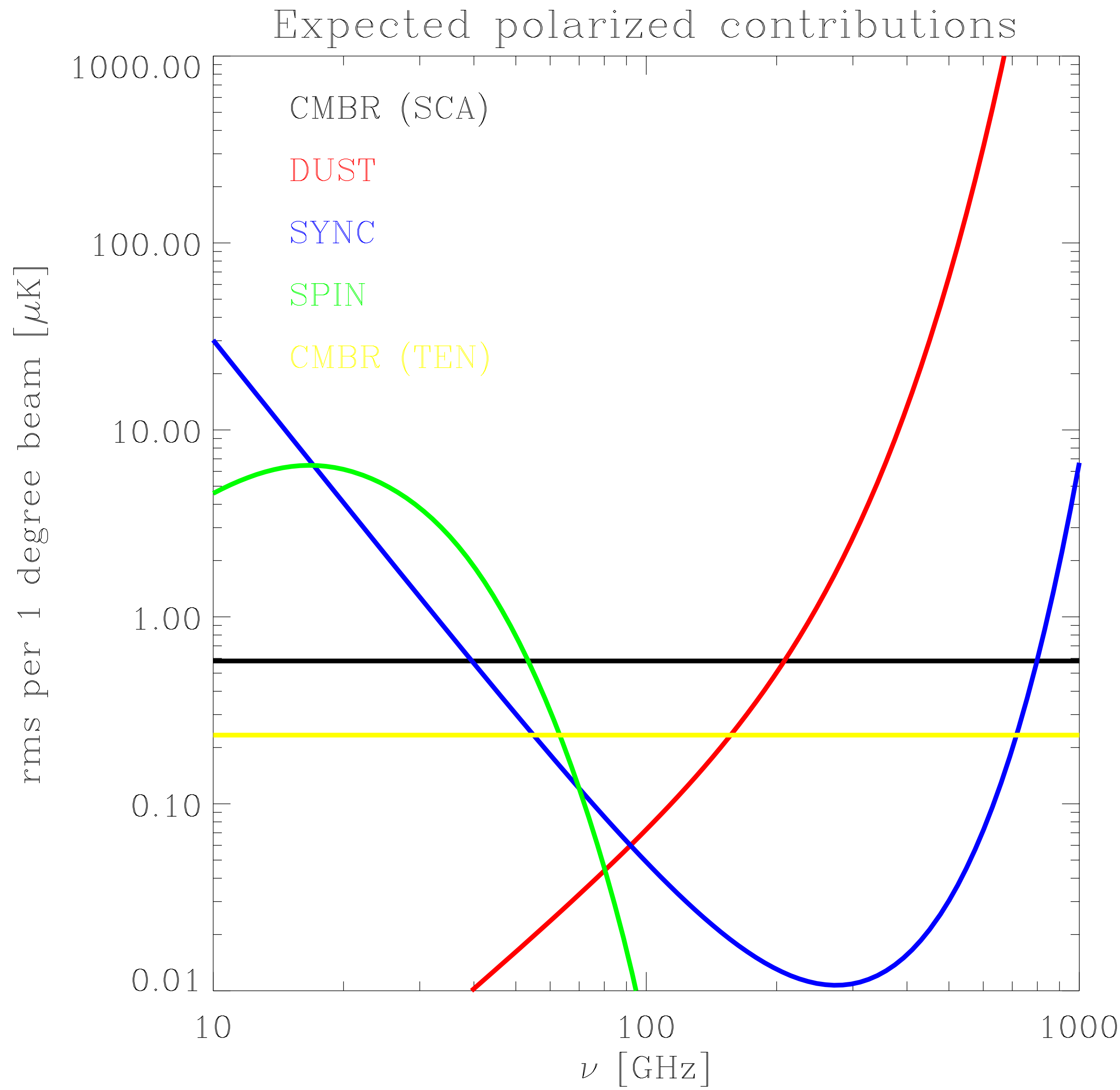
Ongoing measurements of CMB polarization.

Most of these observations will have begun in the next two years, with the exception of the PLANCK LFI and HFI instruments, which are scheduled for launch in 2007. For each experiment, the beam size listed is the smallest, since many of the experiments have beam sizes that vary with frequency.

Experiment	Beamsize (Degrees)	Frequency (GHz)	Receiver	Site
VLA	0.02	8.44	interfer.	NM desert
POLATRON	0.04	96	bolometers	OVRO
PLANCK HFI	0.08	143, 217, 545	bolometers	space L2
PIQU	0.22	40, 92	HEMT	Princeton
PIQU2	$\leq$ 0.2	40, 92	HEMT	high alt.s̃ite
MAP	0.23	22, 33, 40, 61, 98	HEMT	space L2
boomerang2000	???	???	bolometers	l.-d. balloon
PLANCK LFI	0.20	30, 44, 70, 100	HEMT	space L2
POLAR	7	30, 90	HEMT	Madison
COMPASS	$\leq$ 0.2	40, 90	HEMT	high alt. site
SPORT	7	22, 32, 60, 90	HEMT	space
Milano	7, 14	33	HEMT	Antarctica
Milano2	1	33	HEMT	Alps

data from

Staggs, S. T., Gundersen, J. O., & Church, S. E. 1999, astro-ph/9904062



Expected rms contributions of the different polarization mechanisms as a function of frequency. The CMB polarization signals, both scalar- and tensor-induced, are shown for comparison. Spinning dust grains and synchrotron polarized contributions are taken to be 10% of their unpolarized counterpart. From Prunet & Lazarian (1999).

Significance of M4

- Before Planck (2007?) Provide templates for correcting for dust contribution. Prior to 2007 or probably later M4 will be the only instrument that can supply info on aligned grain contribution.

- After Planck (2007?) Planck will measure emission at much lower frequencies. M4 will provide benchmark tests to determine to what extend Planck's highest frequency channels are dominated by dust polarization. Studies of magnetic field in various environments.

- After Planck (2007?) Insight to dust physics by comparing Planck and M4 data.

M4: Inner Galaxy Survey

- Main Goal: Structure of the field, correspondence to density/velocity structure on pc-kpc scales
  - Roles of breakout, bubbles, spiral structure
- Comparison with Polarimetry in other Spiral Galaxies (same as ionized gas or no?)
- What should the shape of the survey be?

- As far as we can figure out--we *cannot* say much about: scale height, field reversals
- Producing polarization map *models* from field models critical

M4 Primary Science Program

Dan Clemens
Institute for Astrophysical Research (IAR)
Boston University

Components

- Milky Way Disk Survey (MWS)
- Nearby, Dark, Star Forming Cloud Complex Survey (DCS)
- Infrared Cirrus Survey (ICS)
- Nearby Galaxy Survey (AGS)
- Guest Investigator Surveys (GIS)
- Performance Verification Phase (PV)
- Calibration Observations (CO)
- Extended Mission Plan (EMP)

Milky Way Disk Survey (MWS)

- Key Science Questions:
  - Q1: What is the structure of the Milky Way's magnetic field in the star forming ISM?
  - Q2: What roles do spiral structure, superbubbles, and breakout play?
  - Q3: What is the magnetic context on kpc to pc scales?
- 1,350 sq degrees survey of the Inner Galactic Disk
  - Longitude range -60 to + 60 degrees
  - Latitude range -5 to +5 degrees
  - Extended blowout region (|b| to 10deg, |l| ~ 30 deg)
- Angular resolution requirements
  - PFOV of order 1.5-2 arcmin
- Sensitivity - Position angle uncertainty under 3deg everywhere
- Wavelengths - ~100 um

Nearby, Dark, Star Forming Cloud Complex Survey (DCS)

- Key Science Questions:
  - Q1: Are magnetic fields central to GMC and cloud formation?
  - Q2: Is B field structure related to cloud axes (spatial, kinematic)?
  - Q3: Do B fields connect from cloud to cloud and into star forming regions within clouds? Unprecidented spatial dynamic range...
  - Test MHD models of turbulence and star formation.
- 25 sq degrees survey of Oph, Serpens Cloud Complexes
  - TBD filling factor (mixed mini-surveys) for larger area
- Sensitivity - Position angle uncertainty under 3deg everywhere
- Angular resolution ~ 1.5-2 arcmin

Infrared Cirrus Survey (ICS)

- Key Science Questions:
  - Q1: Is the B field a dominant organizing force for IR cirrus structure? When is a filament a filament?
  - Q2: Is the B field in the IR dust similar to background starlight.
  - Q3: Is the B field in the IR dust similar to H-alpha (WHAM)
- More area is better, more time is better
  - 2x100 sq degrees surveys
- Angular resolution - 1.5-2 arcmin
- Sensitivity - Position angle uncertainty under 3deg everywhere

Nearby Galaxy Survey (AGS)

- Key Science Questions
  - Q1: What is the B field structure in the dust of M31?
  - Q2: Is the B field related to the IR ring in M31?
  - Q3: Is there a radial field from the M31 center?
- M31 is a good analog for M0, but may be viewed externally
- Survey of M31 - 2x3 degree area
  - arcmin pixels = 21,600 pixels
- Sensitivity - Position angle uncertainty under 3deg everywhere

Guest Investigator Surveys (GIS)

- Targets chosen from orbit segments not allocated to Science Team Surveys
- Extragalactic & Galactic targets
- 5-6 teams
- 12% of Primary Mission science (non-PV, non-cal) time
- Open Call for Proposals 1 year prior to launch
  - NASA (IPAC?) to administer call, selection
  - M4 team to provide ex-officio selection team member
  - M4 team to support GIs
    - direct funding (~100k$ per team)
    - observations planning
    - data analysis assistance

Milky Way Magnetic Field Mapping Mission

Performance Verification (PV)

- Part of early operations (L -> L+30) - Phase D
- Establish attitude
- Test mapping modes
- Test moving parts
- Test all AOTs
- Test on-board data processing
- Monitor satellite temperatures during attitude changes
- Establish safe operating conditions
  - modify AOTs and observing plans accordingly
  - test safe modes
- Evaluate mission success likelihood
- Release aperture cover
- Establish equilibrium temperatures, He flow rates
- Verify Sensitivities
- Communicate findings to Science, GI teams

Calibration Observations (CO)

- Frequent flashes of stimulator (1/20s or so)
- Dedicated calibration observations
  - each orbit (~ 1 segment equivalent)
  - periodically (TBD)
- Astronomical Calibration Sources
  - Source #1:
  - Source #2:
  - Source #3:
- Background/Instrument Calibration
  - TBD

Extended Mission Plan (EMP)

- 50% Science Team
  - Goals:

- 50% Guest Investigators
  - How to select?
  - Targets?

M4 10/22/99: Science from Giannino's

- Parker Instability Test
- "Pearls on a String" view of H II Regions
- Dispersion in **B--**dependence on scale height?
- Can we see "valleys" in Ophiuchus
- LMC in list of GO targets?
- Comparisons with synchrotron polarization.

M4

More Decisions

- Select 2 arcmin pixels
  - Requires rotating waveplate to avoid non-matching areas for Stokes parameters
  - Can we get required instrumental polarization over 1 deg field?

Milky Way Magnetic Field Mapping Mission

DC Thoughts (Post Sleep)

- We must do the galactic center
  - Roger will kill us if we don't
  - One of the only places with detailed B field models for testing!
- Launch Window
  - 6 months are out because Sun is in Galactic Plane
  - *M4 launch window is open from February through July*
- Complexity Reduction
  - reduce GI program 50% in all units (number, cost, mission time)
- Overly Lean FTE count
  - add 2 FTEs to M4/SOC for 3-4 years
  - cost from reduced GI program
- Mission Lifetime reduced by 25%
  - larger pixels means faster mapping
  - cirrus survey to fill more orbit segment gaps (from GI program)
- Shorter Lifetime = smaller dewar, instrument
  - lower mass = lower cost (models primarily based on mass)
- Launch Vehicle
  - Pegasus baselined for proposal
  - Proposal calls out Phase A search for shared ride and cost reduction
    - caution regarding funding caps coming out of Phase A

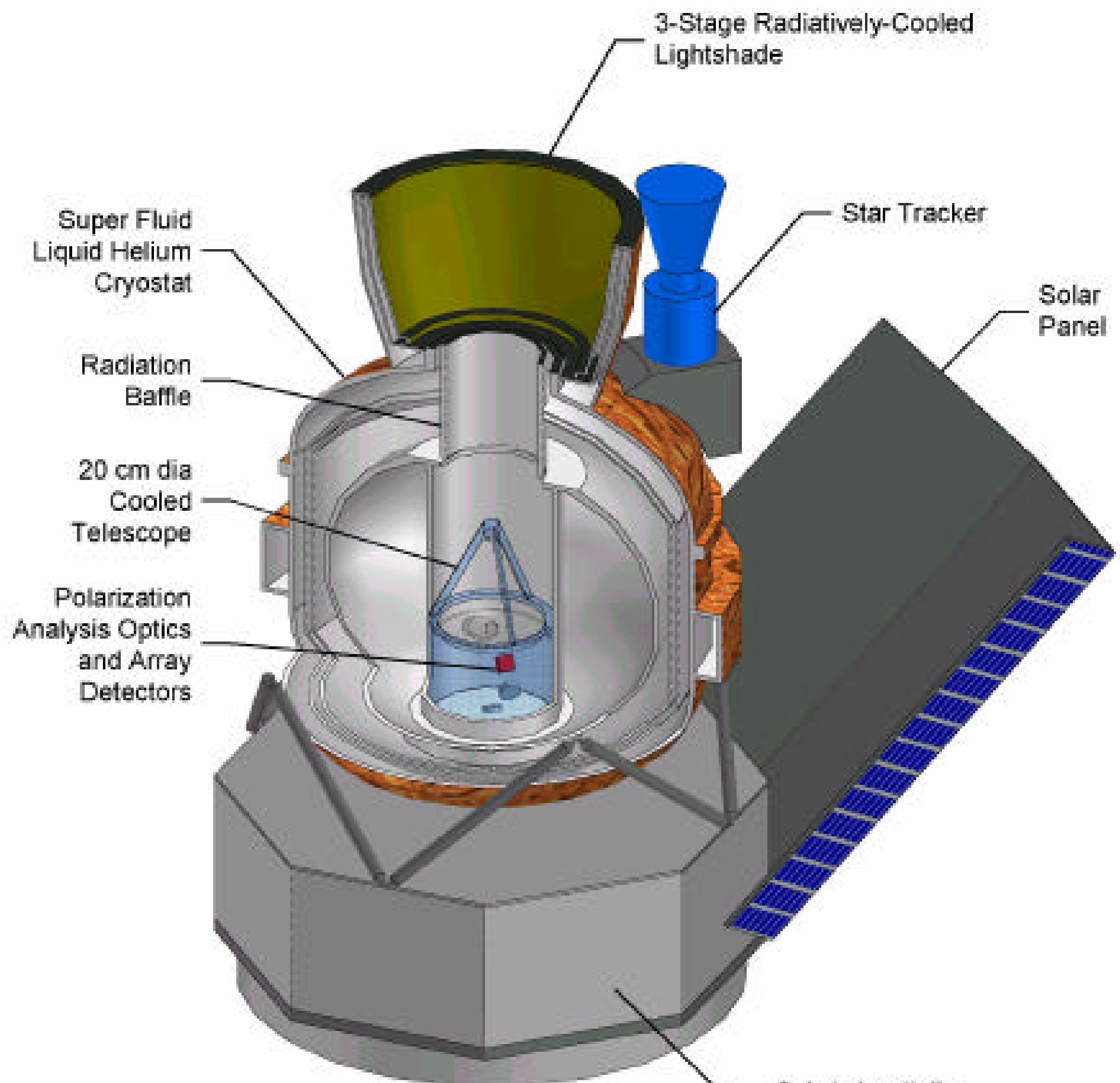
Instrument, Spacecraft, and Launch Overview

Joan Howard

Ball Aerospace

Instrument Requirements

Parameter	Requirement	Features
Waveband	95μm	Matches Available SIRTF FPA's
Detector Angular Subtense	48 seconds	Oversampling diffraction blur
Field of View	~26 minutes	Matches 32x32 current detectors
S/N	Req: 150 Goal: 600	
Cooling	Detectors<2K; Optics<6K	Light shade limiting cryo load on last proposal
Instrument polarization	<1%	Analysis meets
Calibration	<1% source	Use standard source


3-Stage Radiatively-Cooled Lightshade
Star Tracker
Super Fluid Liquid Helium Cryostat
Solar Panel
Radiation Baffle
20 cm dia Cooled Telescope
Polarization Analysis Optics and Array Detectors
3-Axis Inertially Stabilized Spacecraft

Ball Heritage

- Currently building SIRTF CTA and instrument which uses Ge:Ga FPA's
  - Past CDR in subassembly test
  - No major technical showstoppers
- IRAS flying successfully
  - very similar from a cryo design - only smaller
- Conceptually simple design
  - simple electronics, tested FPA's, small/few element optics, but….
  - Cryo design never simple

Spacecraft Requirements

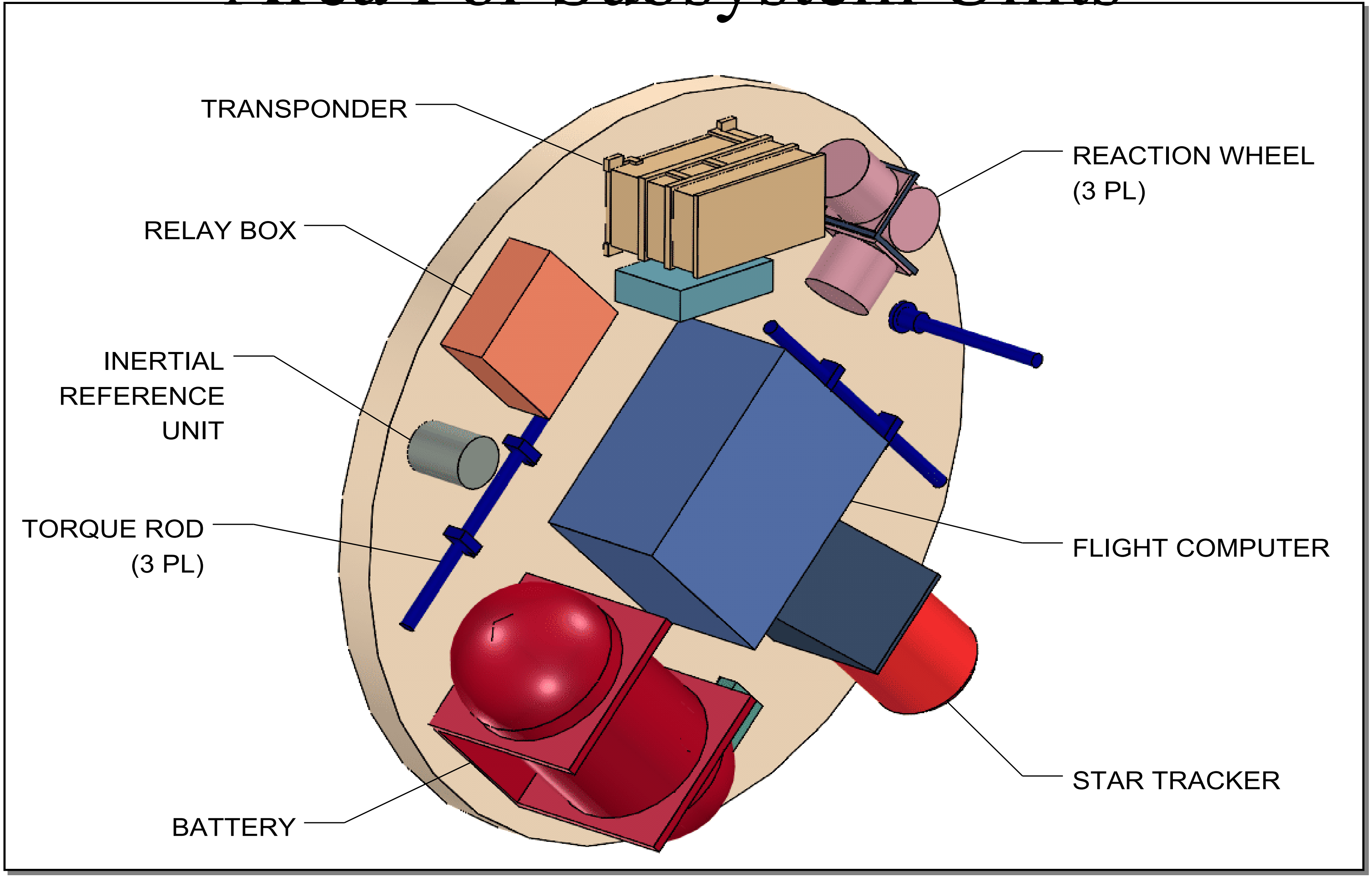
- Low Cost - less than $15M?
- Accept >125 kg instrument
- Provide > 30 Watts of power to payload
- Pointing Stability < 24 seconds per data acquistion
- Fit into selected Launch Vehicle
- Data Storage: 200 Mbytes

Spacecraft Key Performance Requirements

Description X-12M SMEX LITE SA-200S MiniStar

Spacecraft
Bus Mass 65.6 kg 75kg 98kg
Payload Mass
Capability 200 kg 91kg 200kg 180kg
Available
Payload Power > 100 W 150W 60W 17.5W
ACS Configuration 3-axis stabilized 3 axis zero momentum
Gravity Gradient
Attitude
Knowledge 28 µrad 5µrad
.5 degrees
Attitude Control 32 µrad 96µrad 10
degrees
Payload Data
Storage 256 Mbytes 130 Mbytes 8Gbyte
3Mbytes
Communications S-Band S-Band S-band S-band
Telemetry Rate 4Mbps 2.25Mbps 10Mbps 1 Mbps

Equipment Shelf Provides Ample Area For Subsystem Units



S/C Selection

- Meets minimum requirements
- Lowest total cost
  - nearly all COTS buses will need changes
  - integration issues
  - heritage of performance: technical, cost, schedule
- Willing to work with team
- Selection not mandatory for 1st round - *a* solution, not *the* solution needed

Issues/risks/options

- Need good story for aperture cover - esp. after WIRE
- Light shade a key driver in itself and for cryo design
- Star tracker vs. gyro
- battery size vs. eclipse
- CPU capabilities/memory - on orbit computation vs. downlink
- configuration drivers: LV, COTS, star tracker location, timeline, launch date

Launch Options

Option	Pros	Cons
Dedicated Launch	We have more timing control, fewer constraints on design, right orbit	$$$$$$$$$
Share with equal	Workable timing, co-manifest layout, right orbit	How to find the partner, stay coordinated throughout program
Rent a ride	Save $$$$$ - maybe $15M, huge mass margin	No launch timing control, not many LEO opportunities, fewer opportunities that would accept cryo, orbit may be problematic

MIPS Germanium Detectors

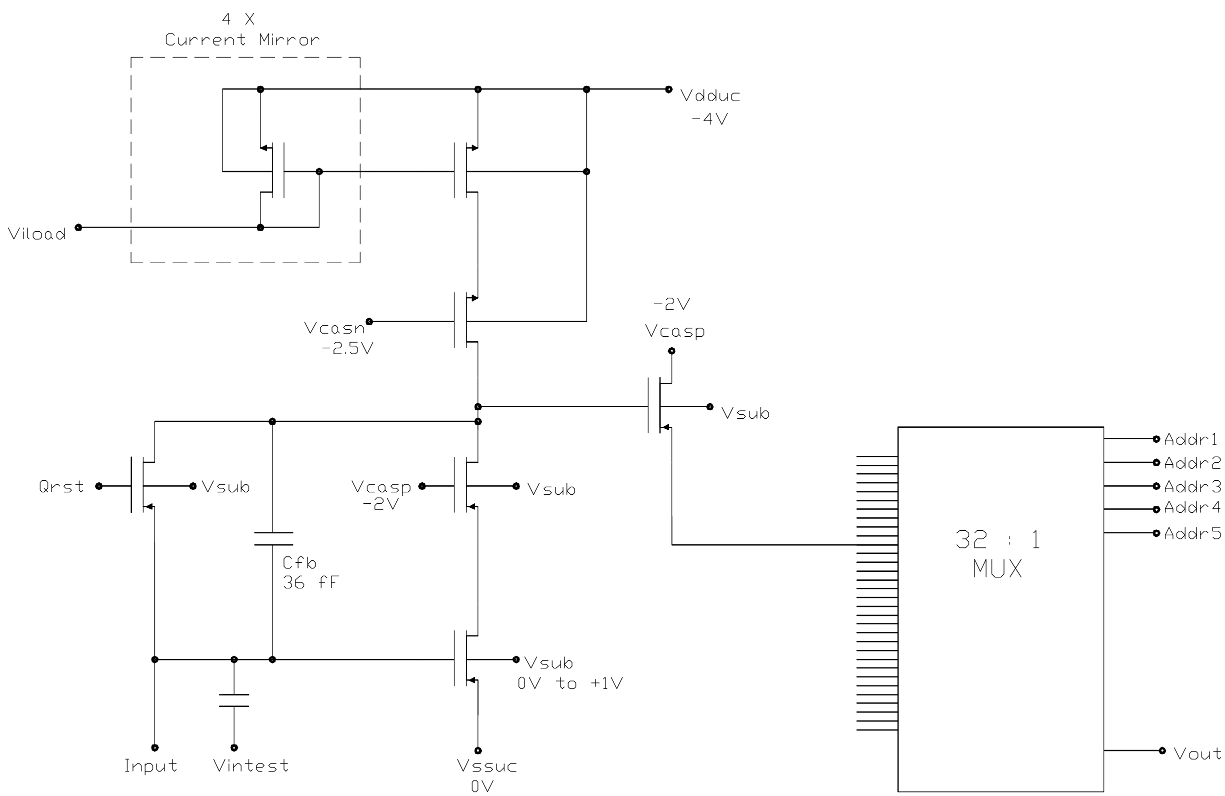
Erick Young

October 22, 1999

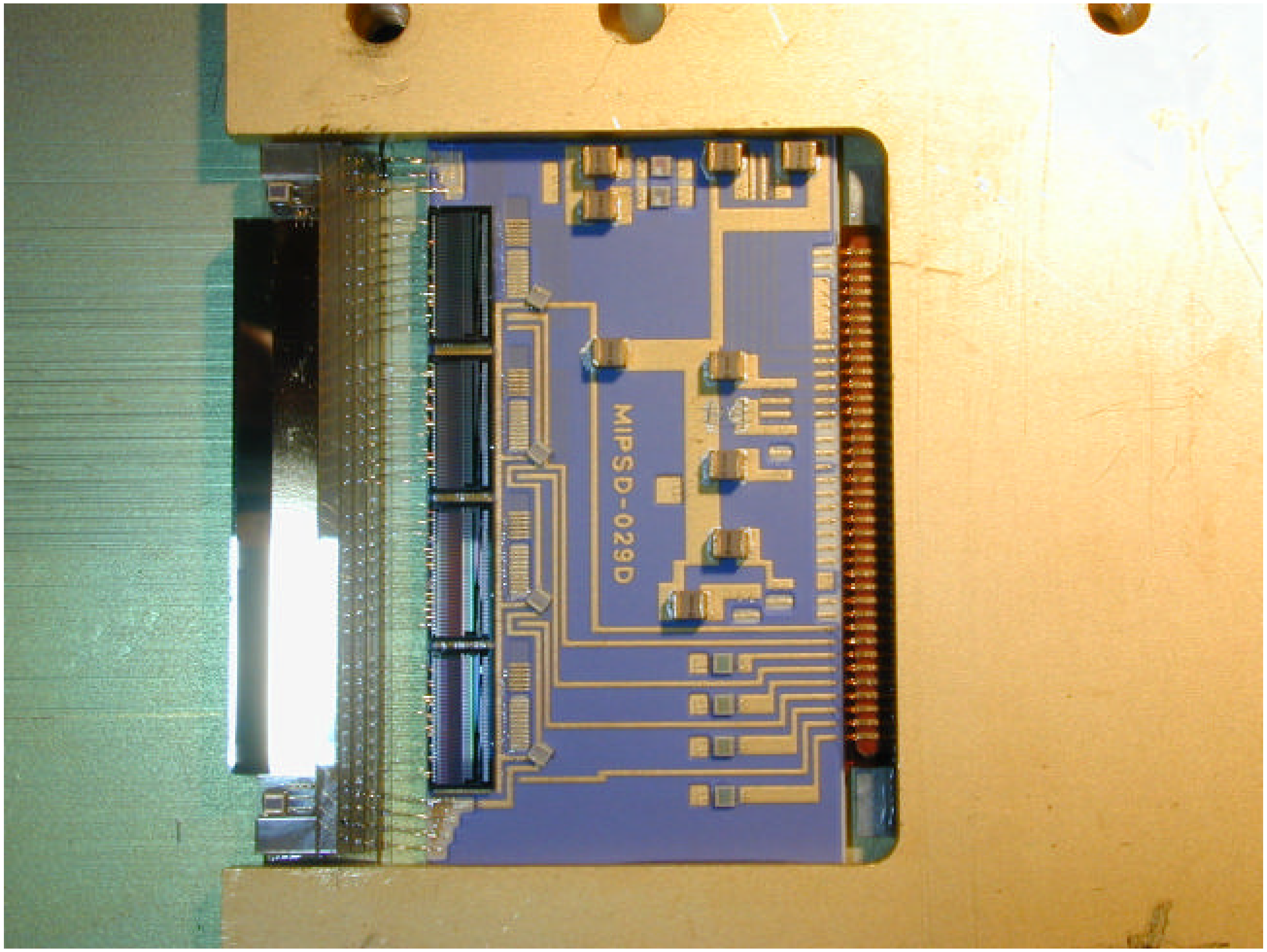
MIPS Detector Arrays

Band	Detector Type	Format	Wavelength Coverage (μm)
24 μm	Si:As BIB	128 x 128	20.5 – 26.5
70 μm	Ge:Ga	32 x 32	60 – 80 50 - 95
160 μm	Stressed Ge:Ga	2 x 20	140 - 180

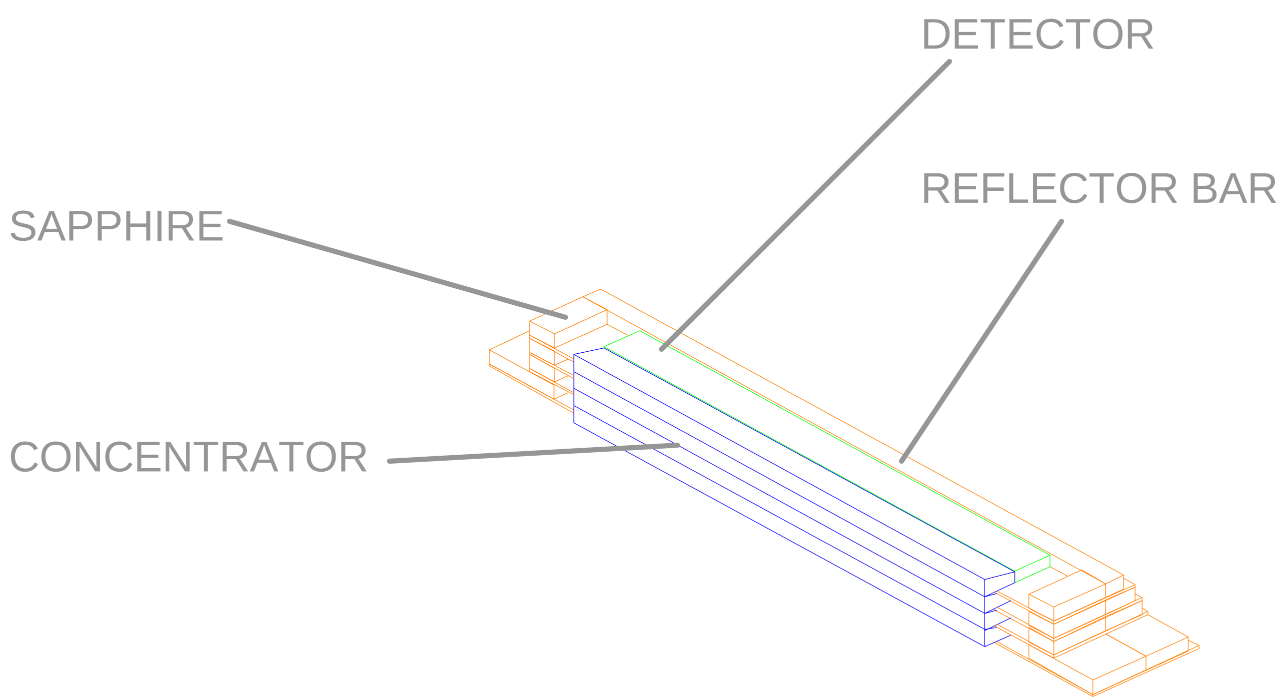
CRC-696 Readout Schematic
Capacitive Transimpedance Amplifier



70 μm 4x32 Array Module Detail



Front End Detail



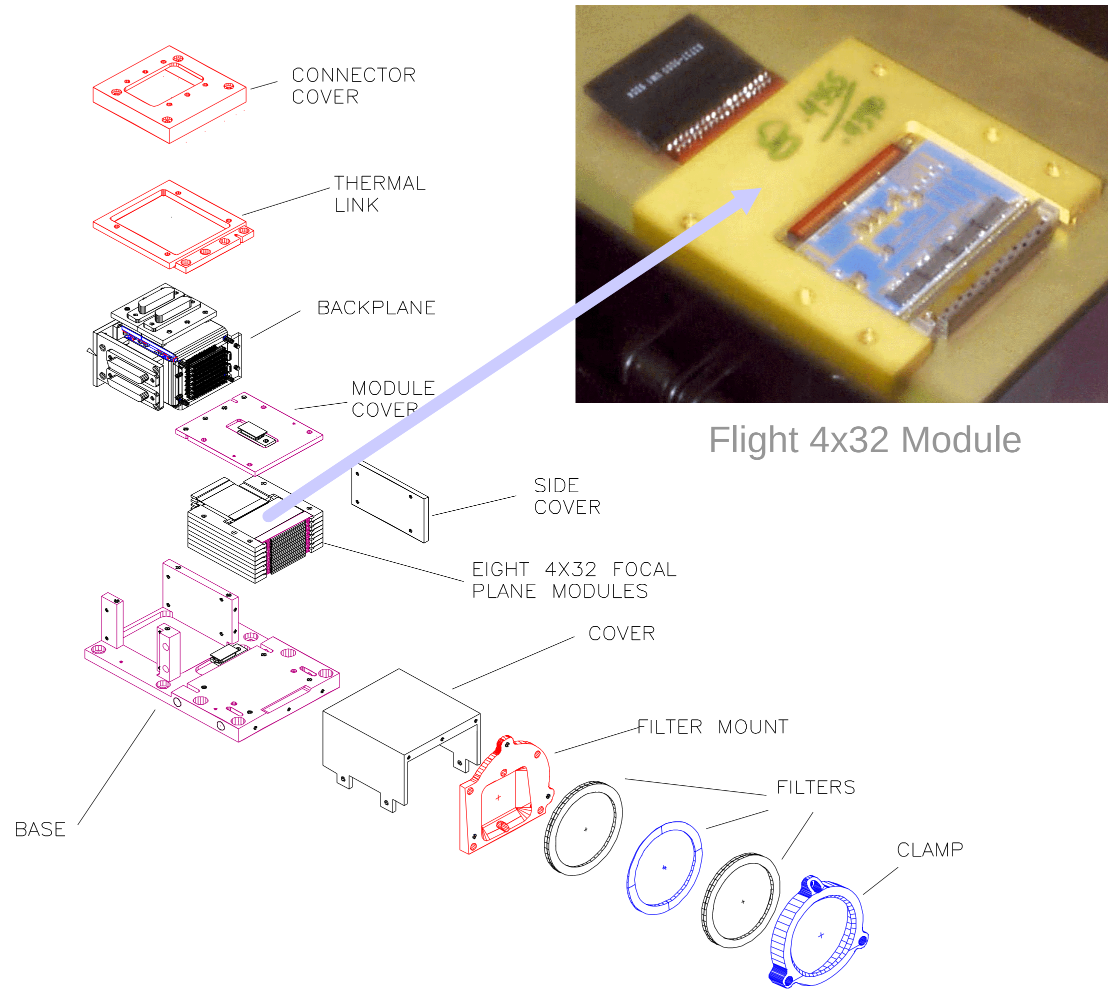
70 μm Array

32 x 32 Ge:Ga photoconductor array

Developed and constructed at Steward Observatory

Detector material from Lawrence Berkeley Laboratory

Custom cryogenic readouts (CRC-696)



Flight 4x32 Module

Pixel Addressing Order

Ge:Ga ARRAY ADDRESSING SCHEME

MODULE 8

4	8	12	16	20	24	28	32	4	8	12	16	20	24	28	32	4	8	12	16	20	24	28	32	4	8	12	16	20	24	28	32
3	7	11	15	19	23	27	31	3	7	11	15	19	23	27	31	3	7	11	15	19	23	27	31	3	7	11	15	19	23	27	31
2	6	10	14	18	22	26	30	2	6	10	14	18	22	26	30	2	6	10	14	18	22	26	30	2	6	10	14	18	22	26	30
1	5	9	13	17	21	25	29	1	5	9	13	17	21	25	29	1	5	9	13	17	21	25	29	1	5	9	13	17	21	25	29

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MODULE 2

4	8	12	16	20	24	28	32	4	8	12	16	20	24	28	32	4	8	12	16	20	24	28	32	4	8	12	16	20	24	28	32
3	7	11	15	19	23	27	31	3	7	11	15	19	23	27	31	3	7	11	15	19	23	27	31	3	7	11	15	19	23	27	31
2	6	10	14	18	22	26	30	2	6	10	14	18	22	26	30	2	6	10	14	18	22	26	30	2	6	10	14	18	22	26	30
1	5	9	13	17	21	25	29	1	5	9	13	17	21	25	29	1	5	9	13	17	21	25	29	1	5	9	13	17	21	25	29

MODULE 1

4	8	12	16	20	24	28	32	4	8	12	16	20	24	28	32	4	8	12	16	20	24	28	32	4	8	12	16	20	24	28	32
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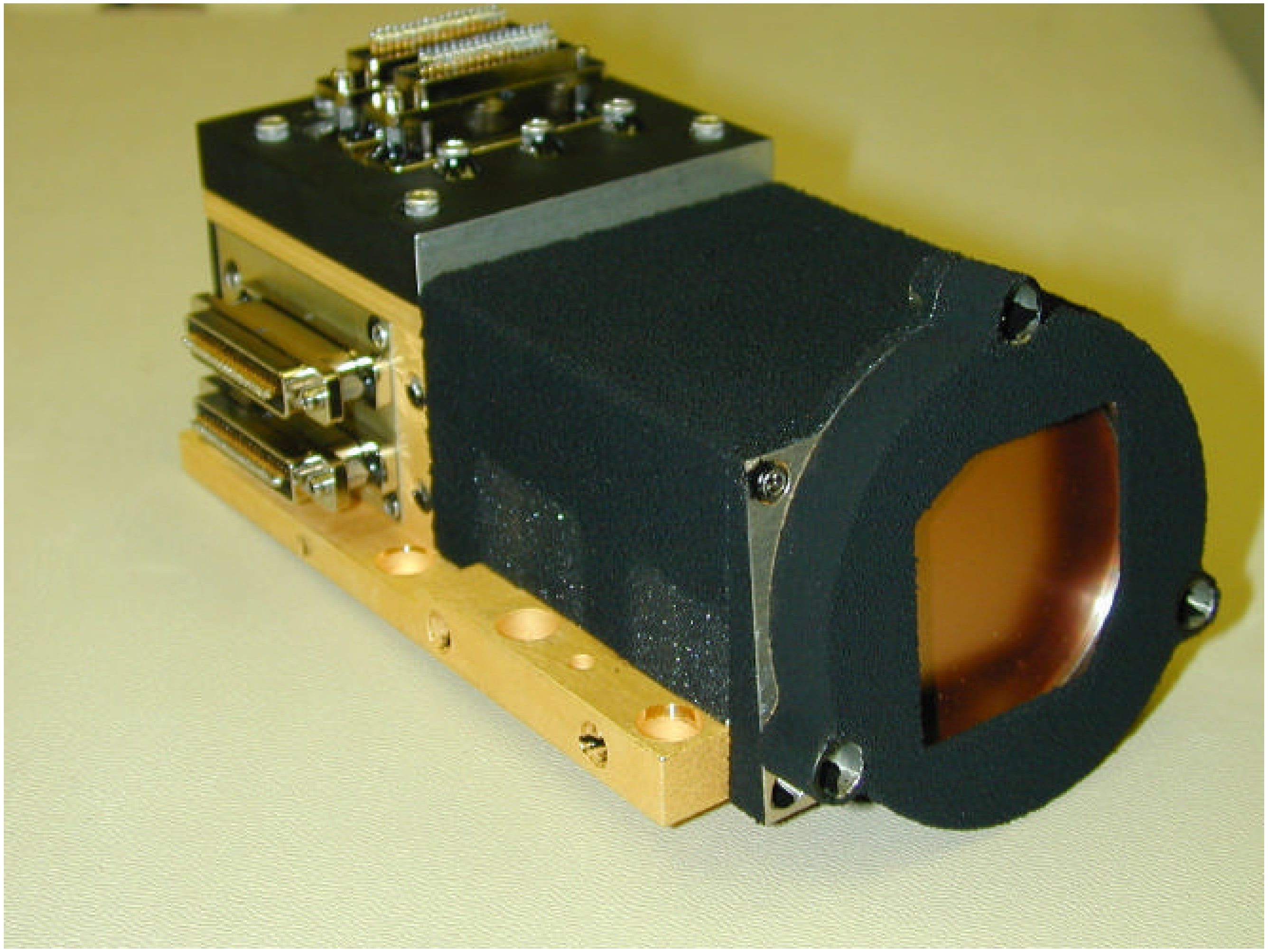
2	6	10	14	18	22	26	30	2	6	10	14	18	22	26	30	2	6	10	14	18	22	26	30	2	6	10	14	18	22	26	30
1	5	9	13	17	21	25	29	1	5	9	13	17	21	25	29	1	5	9	13	17	21	25	29	1	5	9	13	17	21	25	29

BLOCK 1 | BLOCK 2 | BLOCK 3 | BLOCK 4

Flight 70 µm Array



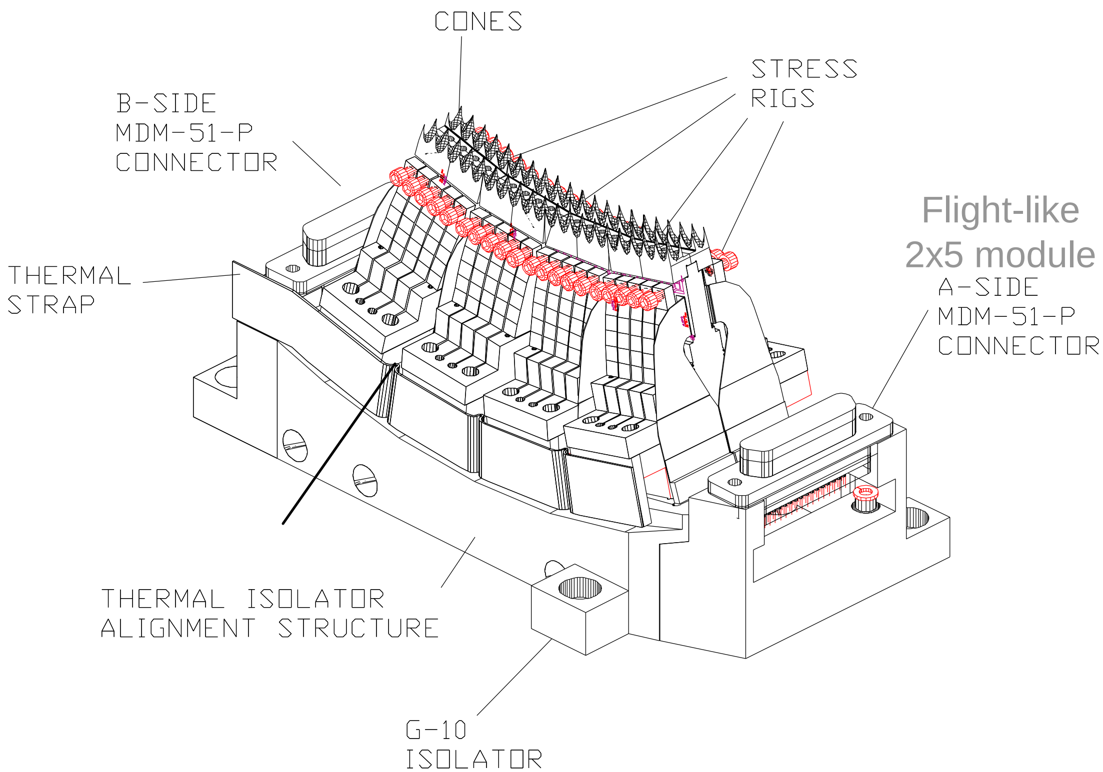
160 μm Array

2 x 20 Stressed Ge:Ga photoconductor array

Developed and constructed at Steward Observatory

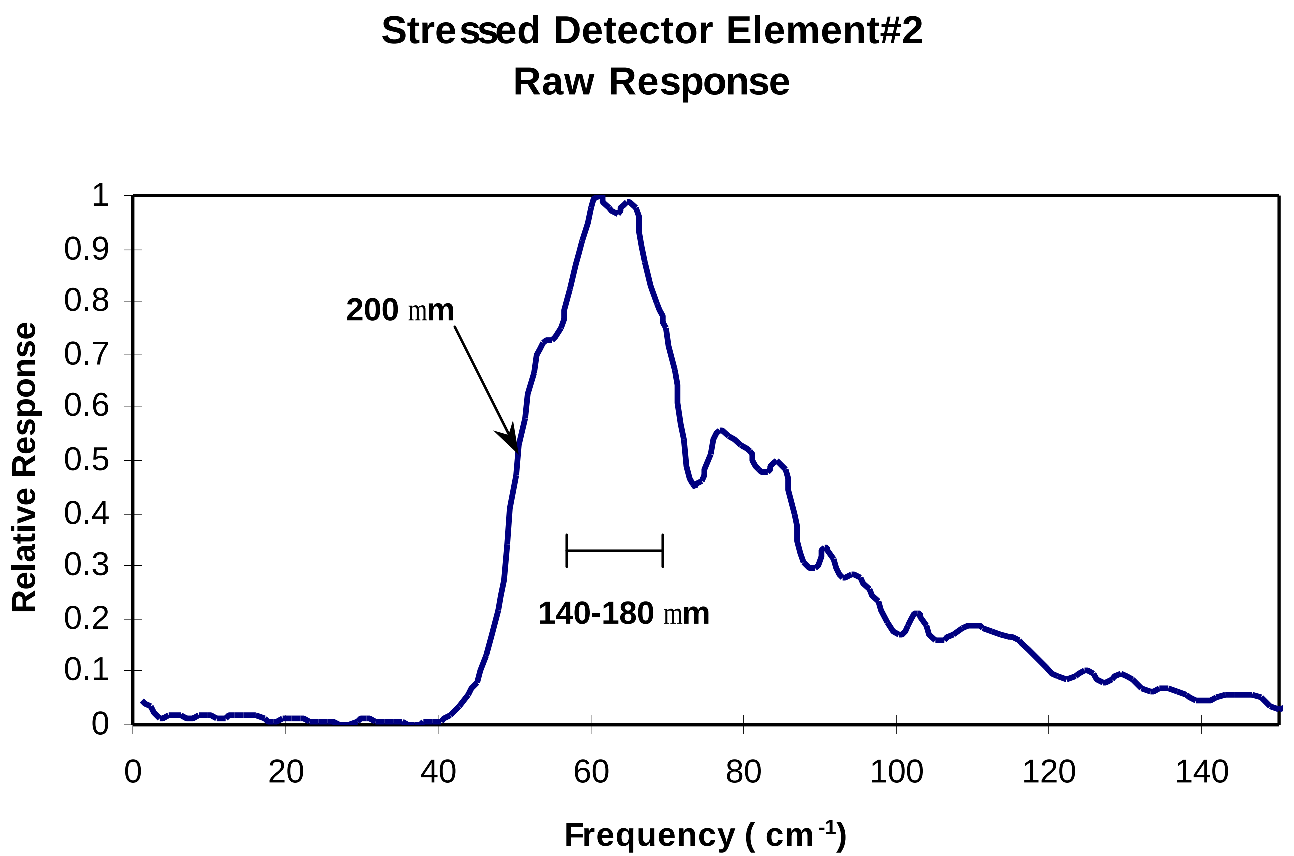
Detector material from Lawrence Berkeley Laboratory

Custom cryogenic readouts (CRC-696)



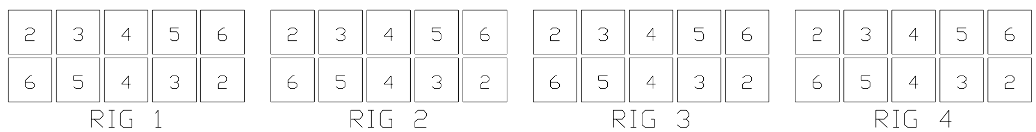
Flight-like 2x5 module

Stressed Detector Spectral Response



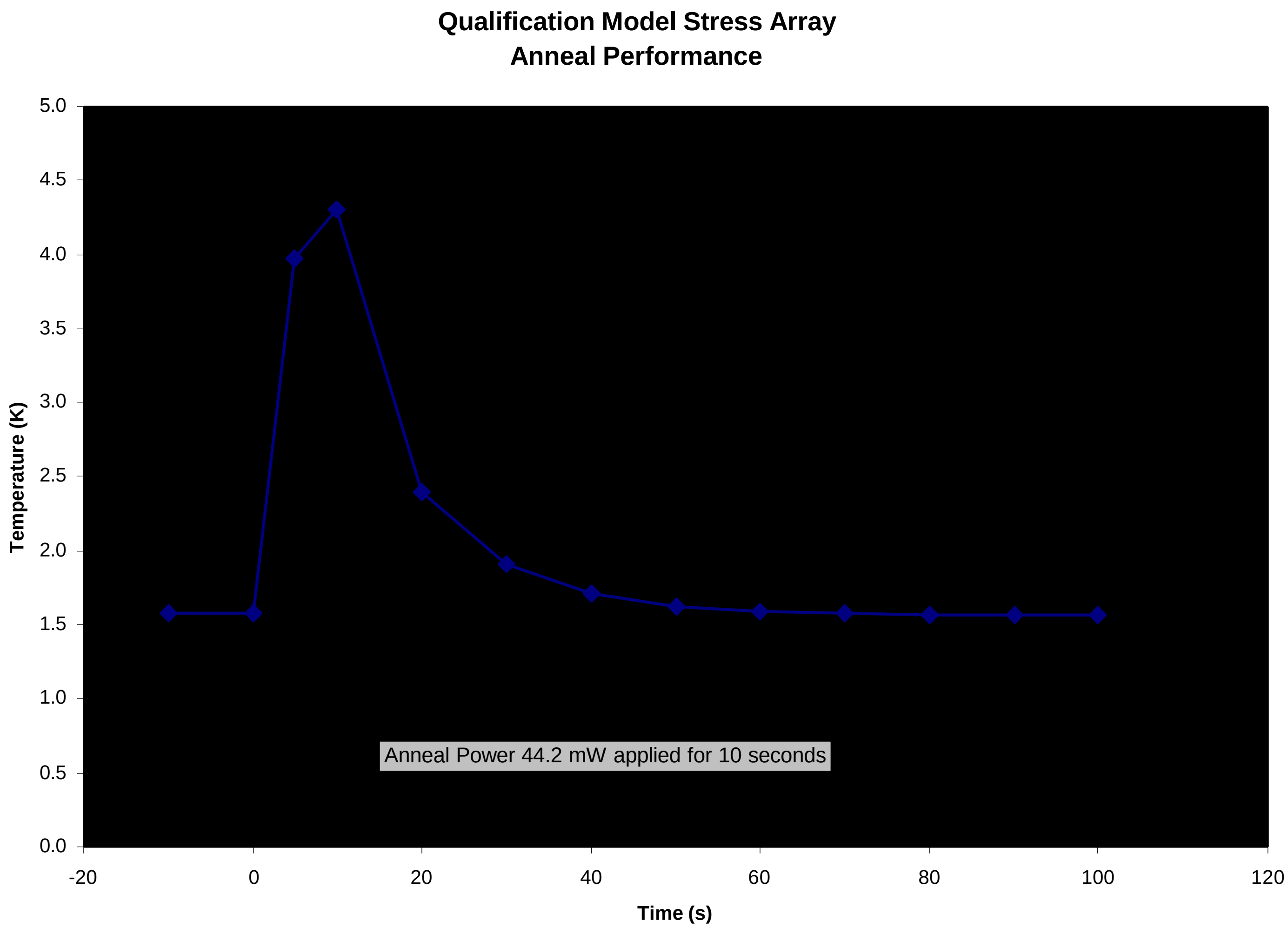
Stress Array Pixel Order

VIEW FROM FRONT OF STRESS Ge:Ga ARRAY



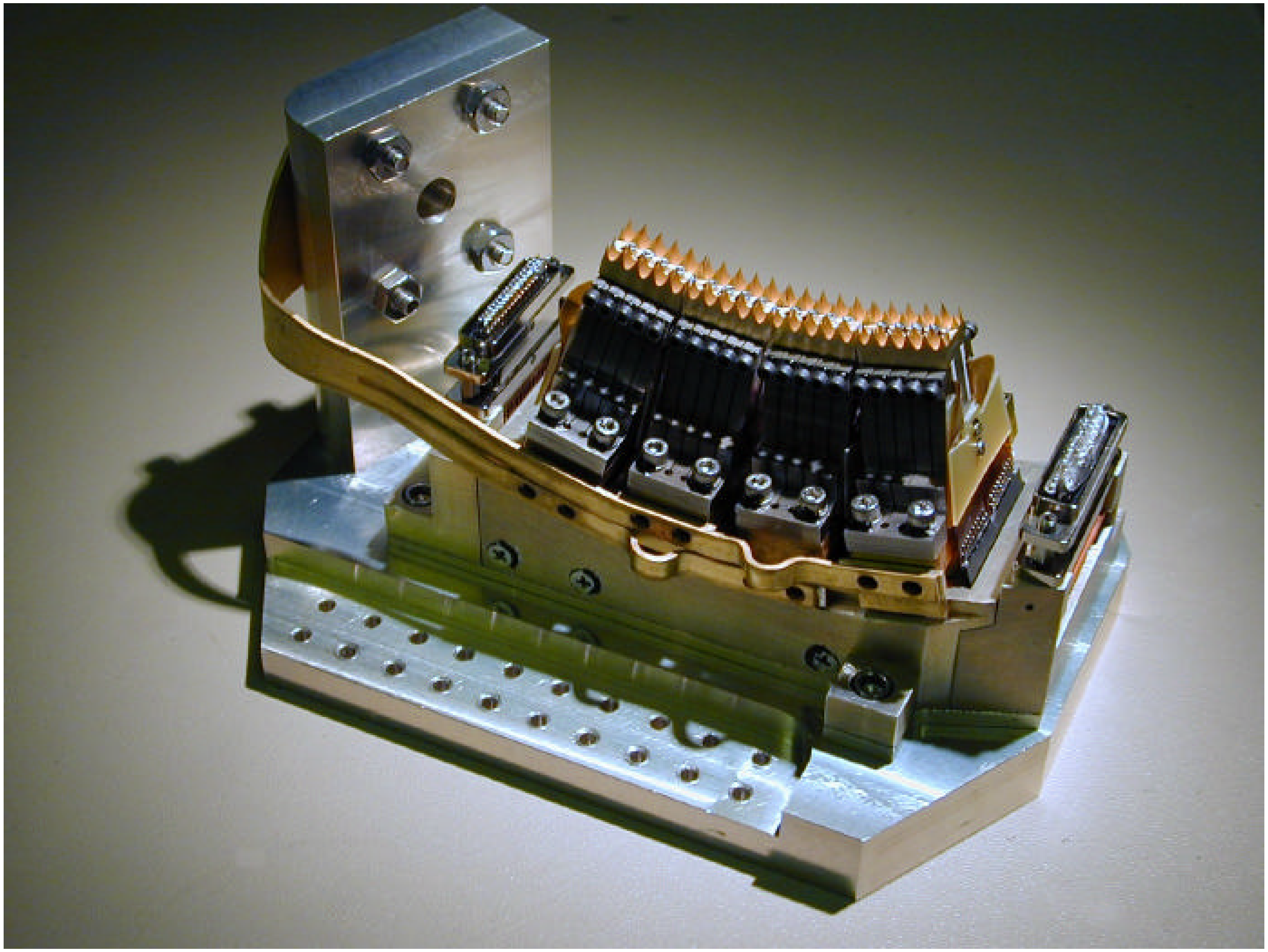
DURING EACH FRAME, EIGHT PIXELS ARE ADDRESSED PER READOUT, BUT ONLY PIXELS 2, 3, 4, 5, AND 6 ARE CONNECTED TO DETECTORS. SIGNALS APPEAR ON EIGHT PARALLEL OUTPUTS. FOR EXAMPLE, ALL PIXEL "2's" ARE ADDRESSED AND AVAILABLE AT THE SAME TIME.

Anneal Test



Qualification Model Stress Array
Anneal Performance
Temperature (K)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-20
0
20
40
60
80
100
120
Time (s)
Anneal Power 44.2 mW applied for 10 seconds

Flight Stress Detector Array



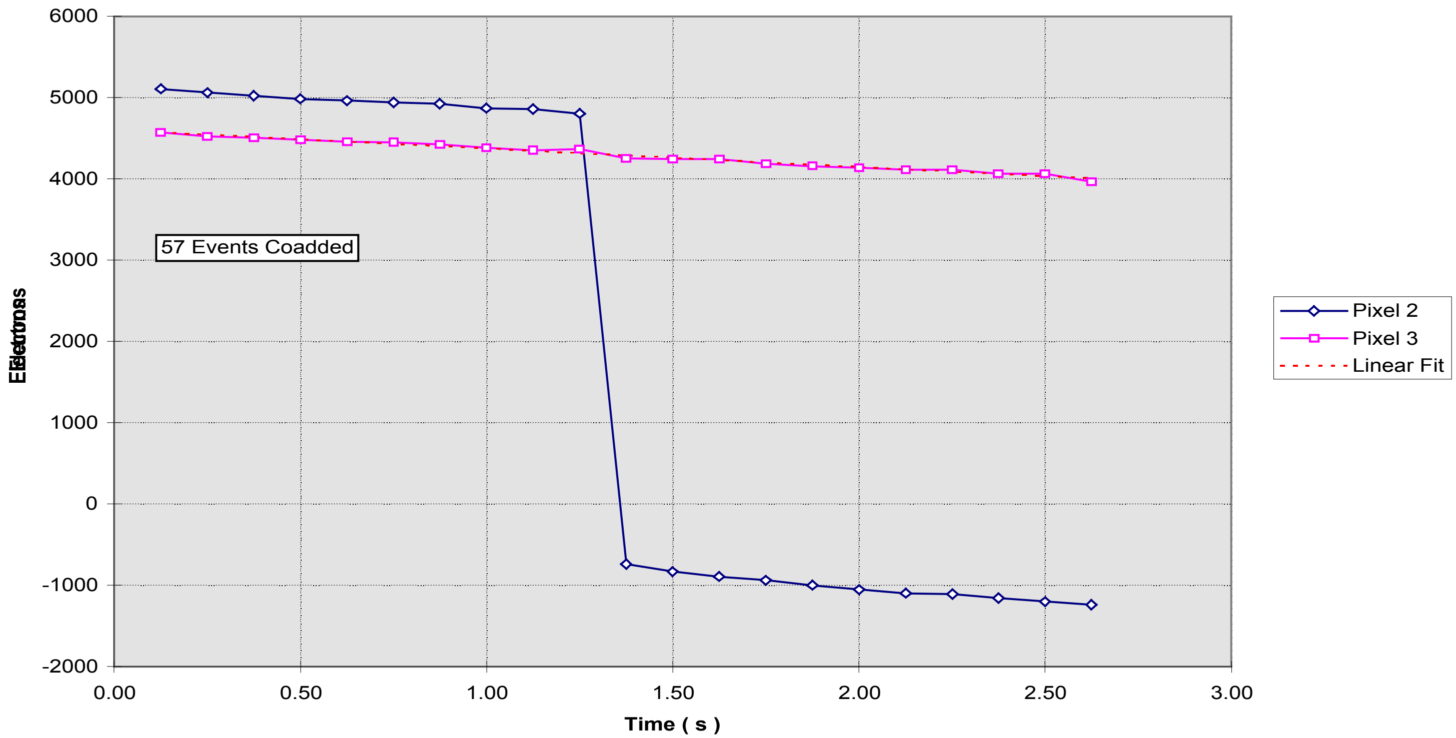
Overall Detector Status

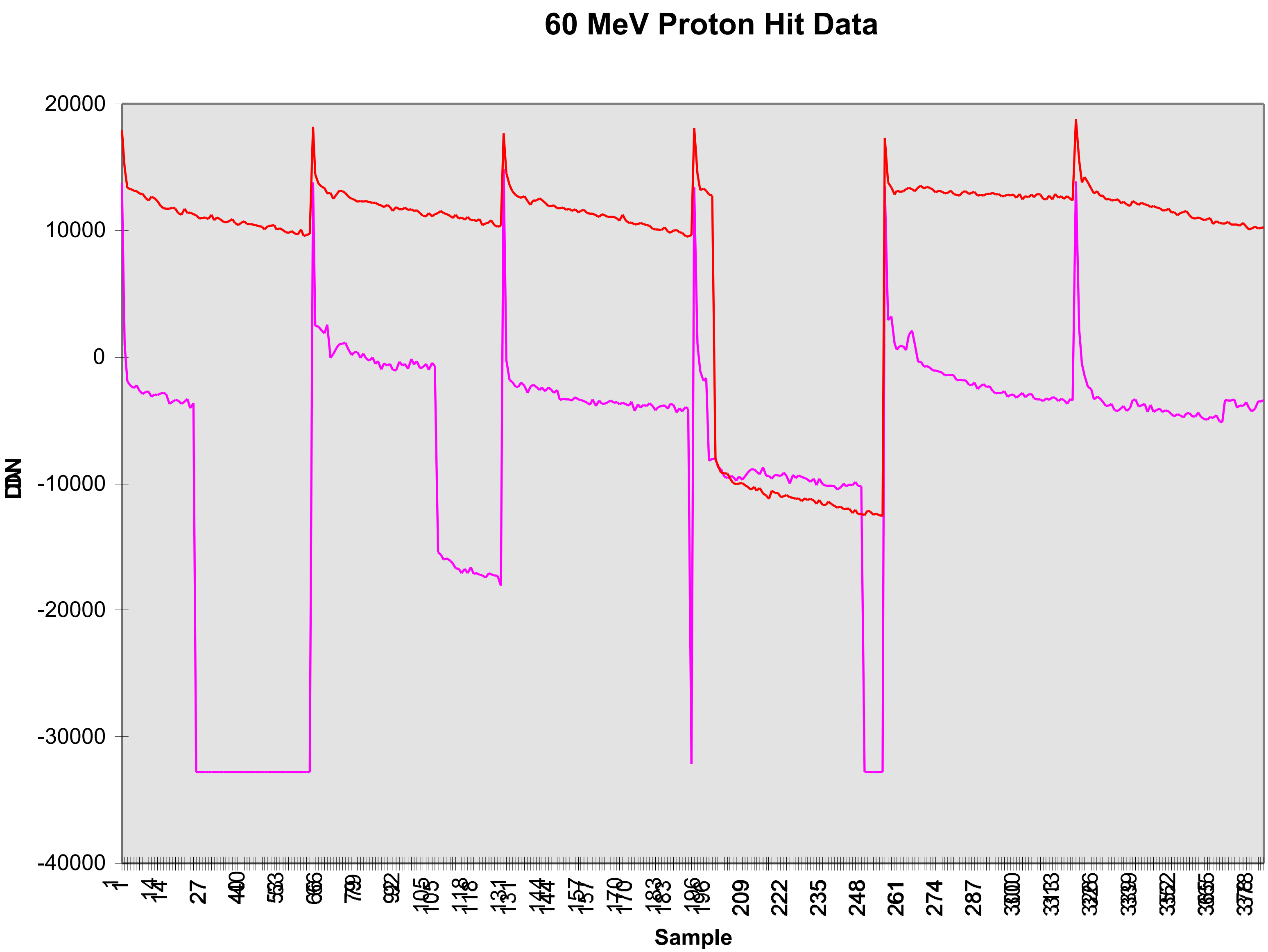
- 24 μm Array
  - *Flight, Spare, and Qualification Units delivered to Ball by Boeing*
  - *Being installed today*
- 70 μm Array
  - *Flight Array has been delivered to Ball and has been installed into instrument*
  - *Flight Spare under construction*
- 160 μm Array
  - *Flight Array has been delivered to Ball and has been installed into instrument*
  - *Flight Spare under construction*

Future Prospects

- Advanced readouts for high backgrounds
  - *SBRC 190 readout has been fabricated to support SOFIA far-infrared arrays*
    - Switchable gains to give full wells 2 x 10^4 to 8 x 10^7 electrons
    - Built in sample and hold to eliminate time skew with rapid readout
- Larger format arrays
  - *64 x 64 Camera for SOFIA*
    - Coverage to 130 μm with Ge:Sb photoconductors

Crosstalk Due to Proton Hit





60 MeV Proton Hit Data
DN
Sample
20000
10000
0
-10000
-20000
-30000
-40000

M4 Management Issues, Structure, Plan

Dan Clemens

Institute for Astrophysical Research (IAR)

Boston University

Outline

- Management Functions
- M4 Management Challenges
- Lessons Learned
- A Draft Management Plan
- M4 Science & Operations Center
- Science Dollars left after M4 construction
- Identifying Key Personnel

Management Functions

- Assume overall Project responsibility (PI function)
  - including recommending termination if science objectives cannot be met within cost/schedule reserves.
- Provide oversight of all units, subcontracts
- Develop, maintain schedule
- Monitor, control cost
- Conduct reviews
- Issue reports (cost,schedule, performance, failure, …)
- Plan, Manage, and Mitigate risk

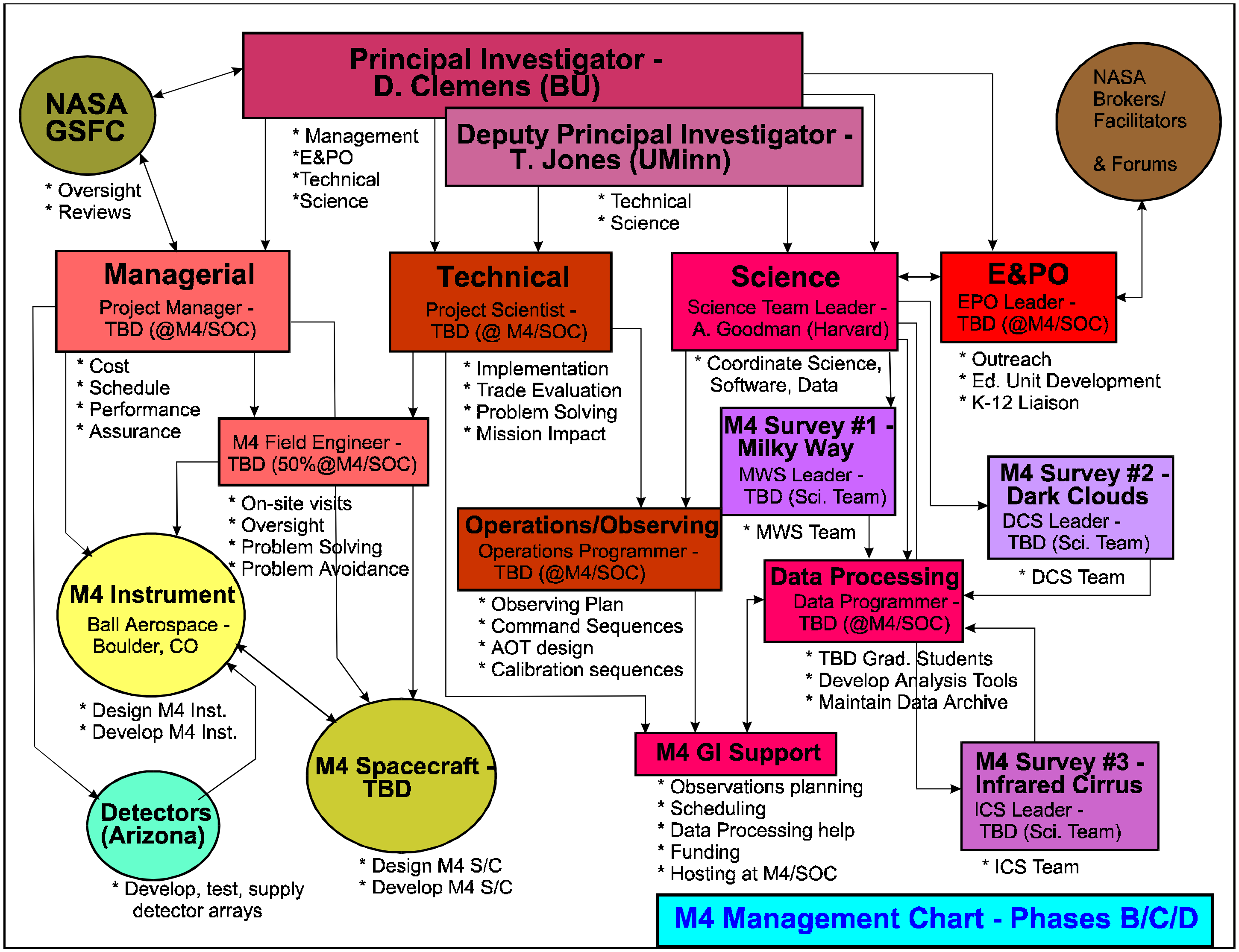
M4 Management Challenges

- M4 Instrument and S/C will both be subcontracts
  - large subcontracts! (~80% of non-rocket costs)
  - how best to oversee Ball and other contractors?
    - avoiding problems
    - solving problems
    - ensuring good communication
- Minimal experience with large project management
  - how best to borrow or buy good management experience?
  - how best to train key personnel?
- Cost control
  - instrument & S/C performance and features
    - which are required? which not?
  - reserve and margin management policy & implementation?
  - preserving MO&DA
    - at "all costs"?
    - priority ranking of MO&DA item value

Lessons Learned

- PIREX and M4/1997 were management challenged.
- PI role in M4/97 was excessively central
  - more delegation necessary
  - more distribution of functions through entire M4 organization needed
- Lean management necessary
  - SWAS model will not work with $$ we have to spend
    - large operations staff
    - long mission lifetime

M4 Draft Management Chart



M4 Science & Operations Center

- Phase A
  - Concept Design
  - Concept Study Report
  - 2 FTE's (PI + PM)
- Phase B/C/D
  - Preliminary Design Oversight
  - Detailed Design Oversight, Data processing & operations development
  - Development Oversight, flight scheduling, testing
  - PI/DPI (DPC part time; TJJ visits, telecons)
  - Management (PM + Field Engineer)
  - Technical (PS + Programmer#1)
  - Science (Science Lead [AG] + Programmer#2)
  - E&PO (EPO Lead)
  - 6 FTE's, 2 PT, graduate+UG students

Milky Way Magnetic Field Mapping Mission

M4 Science & Operations Center II

- Phase E
  - PI/DPI (both full time during flight; part time after flight)
  - PM, FE released after flight
  - PS leads day-to-day SOC activities
  - 5 FTE's during flight, 3 FTE's after flight, + grad&UG students

Science Dollars left after M4 construction

- Total ~9M$ in MO&DA rough budget
- M4/SOC
  - Phase B/C/D cost ~ 2M$ (3yrs @ 5 FTE's ave + hardware)
  - Phase E cost ~ 1.5M$ (4 yrs @ 3 FTE's + travel)
- GI Program
  - 1.3M$ (15 investigations)
- E&PO
  - 0.8M$ (1.6%)
- Science Team
  - 3.4M$ (~12 groups @ 0.75 postdocs for 3 years)

Identifying Key Personnel

- Project Manager
- Field Engineer
- Project Scientist
- Operations/Observing Programmer
- Data Processing Programmer
- E&PO Leader
- M4 Survey Leaders
  - MWS Leader
  - DCS Leader
  - ICS Leader
- M4 Survey Teams
  - MWS Team
  - DCS Team
  - ICS Team

M4 Implementation Issues

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Outline

- We do not need to start over - M4/97 as a basis for M4/99
- M4/97 Implementation
  - Instrument
  - S/C
  - Operations
  - Data
- M4/97 Weaknesses
- Delta's - M4/99 Improvements over M4/97
- Remaining "Tall Poles" & Risks
- Remaining Trades & TBDs
- Appendices -- Why things are the way they are in M4

Don’t start over - M4/97 as a basis for M4/99

- M4/1997 nearly made it into the “final dozen” of 50+ proposals
  - Highly rated science
  - Highly rated implementation
- M4/1997 proposal did a good job of “following the data”
  - from source flux
  - to detection
  - to observing modes
  - to data compression
  - to downlink
  - to data processing
  - to science analyses
- Let’s start with M4/97 and look for places to improve

M4/1997 Implementation

- Instrument
  - Telescope & Cryostat
  - Detectors
  - No-moving-parts imaging polarimeter
- Spacecraft
  - 3-axis stabilized SWAS-like
  - gyro-less
  - performance well-matched to instrument requirements
- Operations
  - satellite roll & orbit segments - polarimetry on the cheap
  - only 3 observing templates (AOTs) needed
- Data
  - detector readout
  - calibration issues
  - charged particles
  - uplink/downlink

Instrument

- Telescope
  - 20cm = largest telescope primary diameter to fit inside dewar
  - cooled to 5-6K with effluent He gas
  - 120 arcsec diffration limit at 95um
- Cryostat
  - "STD" - SIRTF Technology Demonstration dewar
  - never flown, but strong flight heritage
  - modern design
  - required significant redesign to contain M4 telescope
    - STD designed w/o telescope in mind
- Detectors
  - Ge:Ga photoconductors
  - SIRTF/MIPS instrument derived
  - good FIR performance
  - high pixel count - twin 32x32 arrays
  - modest temperature operation for background-limited performance
    - 2K (vs < 0.3K for bolometers)
  - multiplexed readouts for low focal plane heat load

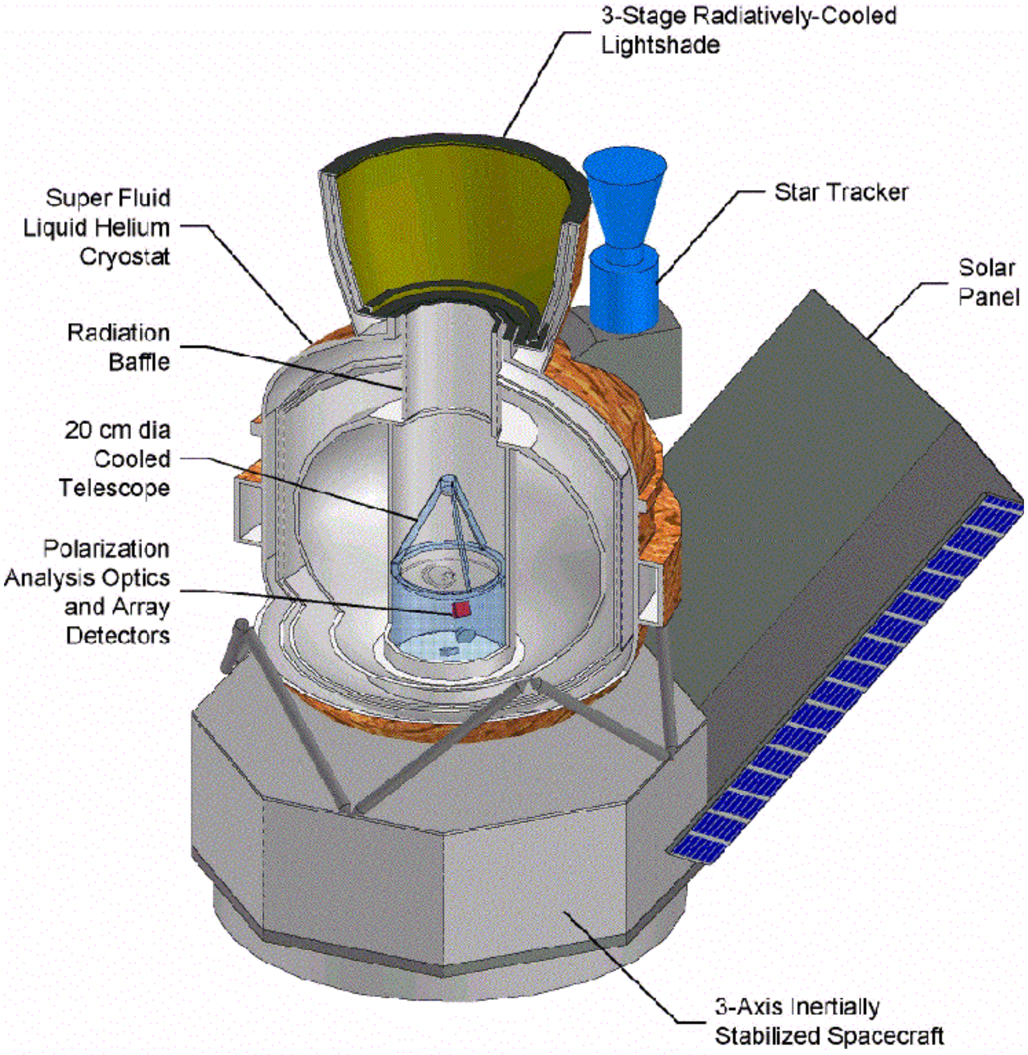
No-Moving-Parts Imaging Polarimeter

- Cassegrain telescope
- Wire-grid beam splitter
- Twin detector arrays - each sees opposite polarization sense
- Satellite roll about bore sight direction
  - fixed 45 degree orientations through one orbit “segment”
  - follow orbit around Earth as a series of segments & rolls
  - detectors for “ISS” = Instantaneous Single Stokes parameters at each orientation
  - 45 degree roll to another orientation turns “U” -> “Q”
  - more rolls turn “Q” -> “U*” and “U*” -> “Q*”
    - * values have detector number switched to remove systematics
- Full observation consists of four orbit segments

Spacecraft

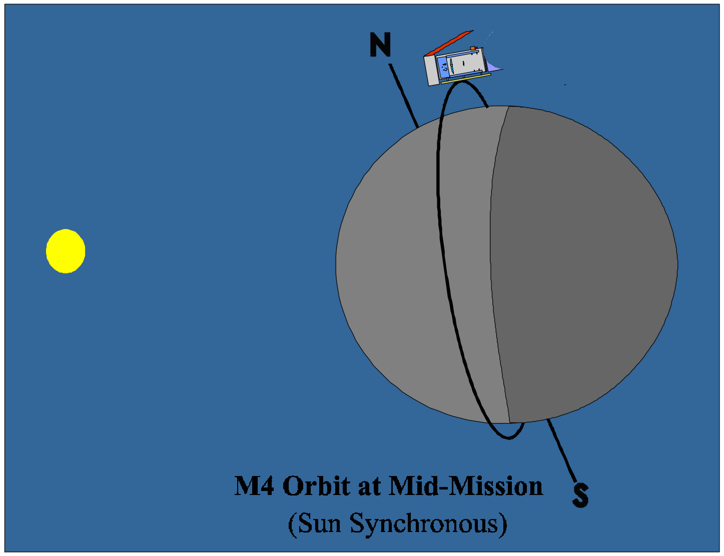
- 3-axis stabilized (SWAS, WIRE like)
- Modest pointing, tracking, jitter requirements
  - beamsize is 120”, pixel size 48” so pointing, jitter less than 20” fine
  - don’t need most expensive star tracker
  - don’t need gyros!
    - big weight savings
    - Ball CT-631 star tracker can develop all finding, pointing information needed
- Must slew between pointings moderately quickly to make raster mapping efficient
  - 11 seconds
- Must develop good electrical power
  - 150-170 watts
- If orbit and launch date selected properly, won’t be eclipsed by Earth during Helium lifetime
  - batteries only needed through launch event
  - mass savings

M4/1997 Satellite Configuration

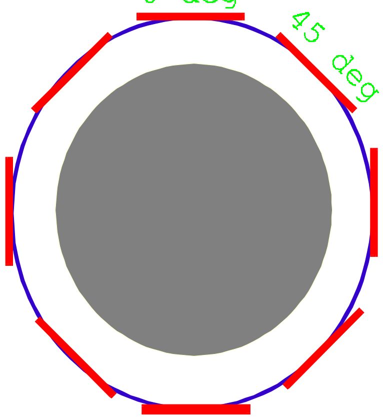


M4 Operations

- Sun-sync orbit
  - dawn-dusk
  - viewing “back” from the orbit
  - Sun avoidance 92deg
  - Earth avoidance 52 deg



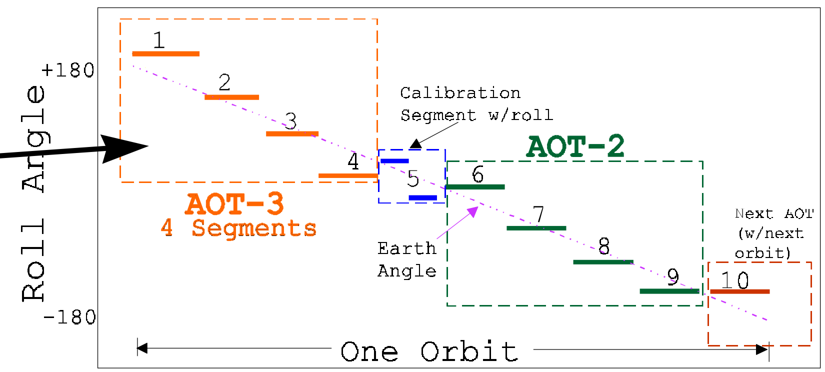
- Orbit Segments
  - 8-12 per orbit
  - 45 deg roll between
  - fixed orientations during each segment
  - 8-12 min segments



Observing Templates

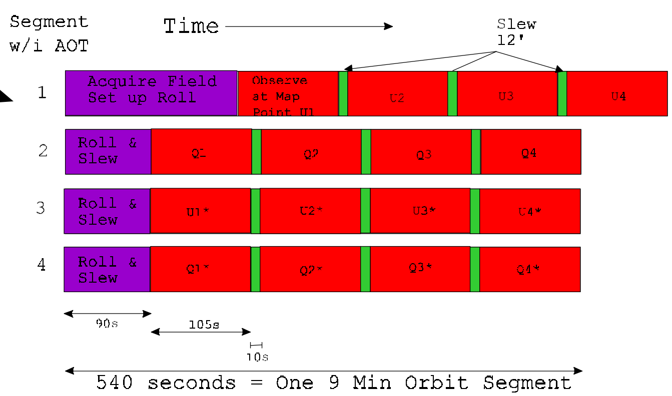
- Only need 3 AOTs
- Hierarchical
  - 4 segments

M4 Orbit: 10 Segments per Orbit



  - N x M raster pattern

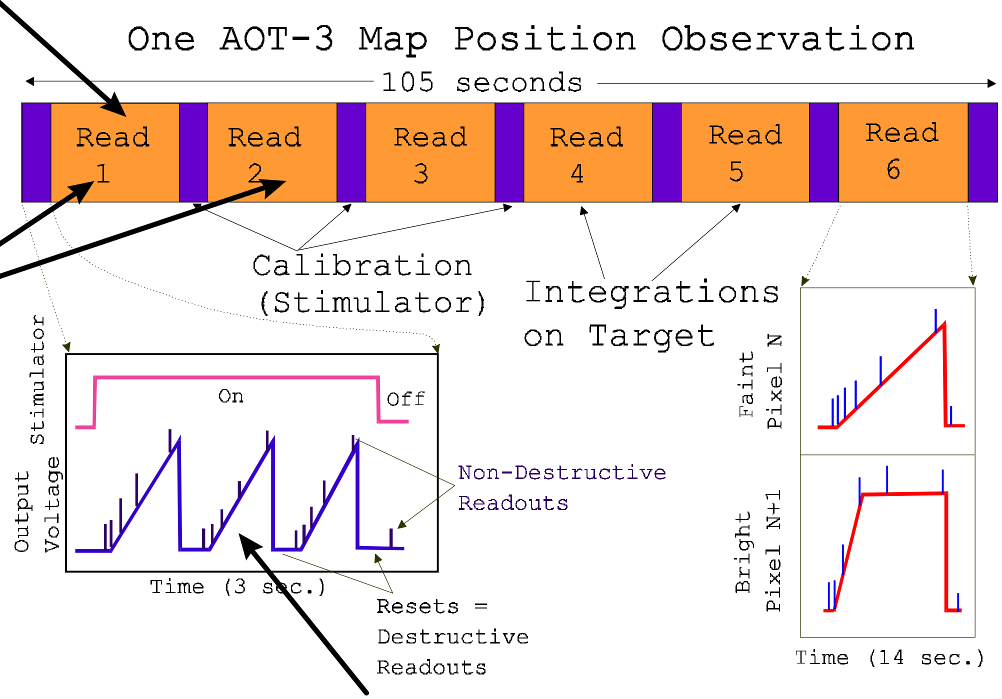
AOT-3 Observing Plan



Operations II

– Fixed integration times

– Multiple integrations per pointing



– Interspersed Stimulator flashes for Calibration

Data flow

- Preserve 600:1 S/N for all scene illumination levels
  - lowest level -> Cirrus = 1 MJy/sr target SB
  - highest level -> Galactic Center = 20,000 MJy/sr target SB
  - lowest NESB = 0.2 MJy/sr
  - maxium dynamic range = 600 * 20,000 / 0.2 = 60 million!
    - but don’t need all of this -> GC is target noise limited, not background
- Split up dynamic range across units
  - detector well depth
  - ADC conversion gain
  - AOT integration times
  - Raster map overlaps and resamples
  - Orbit segment redundancy
- Conversion gain to oversample noise in background limit
  - 0.02 MJy/sr/ADU

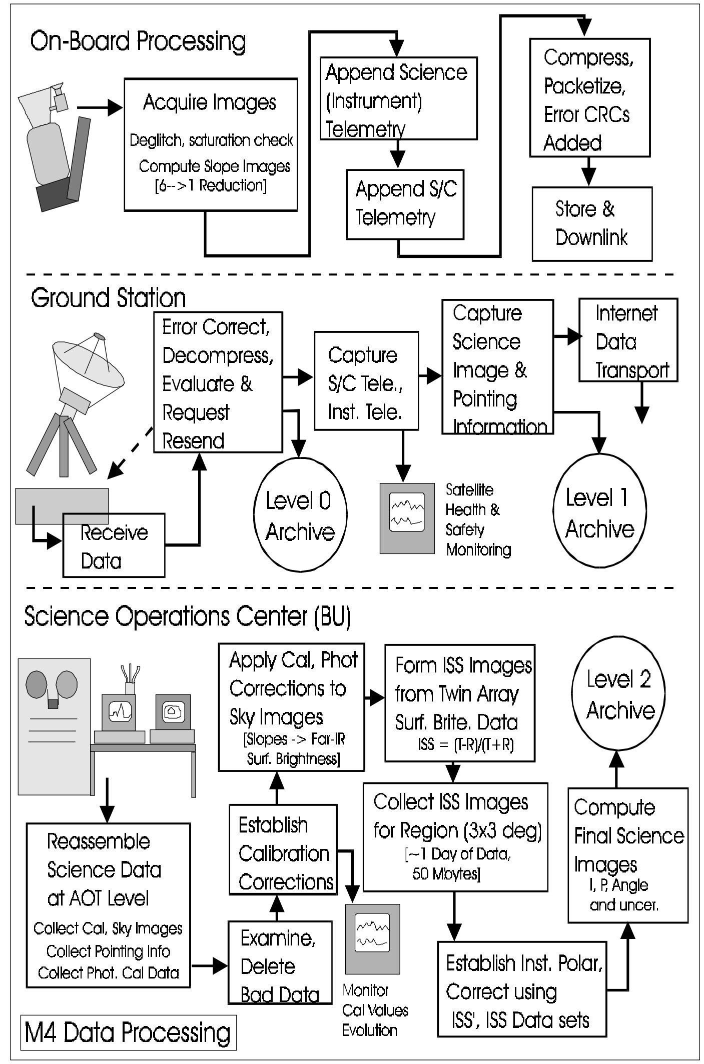
M4/1997 AOTs

- AOT Summary

	AOT-1	AOT-2	AOT-3
T(int.) [s]	0.15	1.5	14
Reads/map point	33	6	6
Cal Rate [1/s]	1/20	1/6.5	1/16
Map raster	5x5	4x4	2x2
Area/4 seg [sq.deg.]	1.13	0.73	0.18
Eff. ISS T(int) [s]	40	72	672
Data Vol./AOT [Mb]	6.1	1.7	0.8
Survey Application	G. Center, Plane	G. Plane, Dark Cl.	Cirrus, Galaxies

Data Flow

- Use “standard” NASA uplink and downlink services
  - No dedicated M4 ground station
    - reduced cost
  - Limited to <6min downlink per day
    - must compress data before downlink
    - must deglitch on-board
  - Must operate in robotic mode for 1-3 days w/o uplink
    - must store up to 3 days of data for all AOT mixes



M4/1997 Weaknesses

- Needed 4 consecutive “segments” to obtain full Stokes parameter set
  - U, Q, U’, Q’
- 92 deg Sun avoidance
- 52 deg Earth avoidance
- size of region which could be viewed by 4 segments --> 0
  - originally had 8 segments per orbit
  - even with 12 the 4-segment overlap was exceedingly small
- ISO PHT polarimetry experience
  - worked, but…
  - responsivity drifts on many time scales
  - need to cycle through polarization position angles many times
    - two cycles through 3 wire grids inadequate

Delta's - M4/99 Improvements over M4/97

- M4/1999 must have a "rapidly" rotating half-wave plate
- M4/1999 needs a larger instrument Field of View
  - Wider is generally better for mapping
    - Faster mapping
    - More sensitivity to faintest surface brightness levels
  - Wider is harder for telescope, collimator, halfwave plate, camera mirror designs
    - Makes mapping brightest scenes (Galactic Center) harder
      - must readout even faster to avoid saturation
  - 20 cm aperture, 95um PSF = 2 arcmin
  - 1997 - identified superresolution as a goal
    - PFOV 48 arcseconds
  - Optimum M4/1999 PFOV?
    - 75 arcseconds gives instrument FOV of 40x40 arcmin
    - ISO PHT at 160um was 92 arcseconds (and 3x3 arcmin)

Delta's II

- Wavelength Choice and Number
  - M4/1997 was 95um, twin detector arrays
    - redunancy and no light loss (looked at refl & trans beams from wire grid beamsplitter)
  - Longer wavelengths are better
    - more sensitivity to cooler dust
  - More wavebands is better
    - measure relative warm vs cool dust contribution to polarization
  - M4/1999 -> 2 wavelengths, still only two arrays
    - 90um 32x32 detector (refl beam)
    - 110um 32x32 detector (trans beam)

Remaining "Tall Poles" & Risk areas

- Ge Photoconductor Detector operations
  - Charged Particle Hit Rate & Responsivities
- Data collection issues
  - Photometric Data Collection - AC or DC?
  - Stimulators, Stability, and Polarimetry
  - Polarization Calibration
  - Stokes Mapping
- Cryogenic Issues
  - Thermal Management & Orbit Segments
  - Forward Light Shield
  - Cold Heat Loads
- Failure Modes
  - Gyro-less operation in the post-WIRE world
  - Batteries, solar panels, eclipse seasons
  - Aperture Cover Issues
  - Rotating Half-Wave Plate - Motors, gears, mechanisms

Remaining Trades & TBDs

- New M4 Orbit/operations model
- Detector operations model
- Data collection, compression, processing model
- Updated Thermal Model(s)
- Full Optical Design with half-wave plate
- Scheduling/observations planning tool

Appendices -- Why things are in M4

- Orbit & Lifetime
- Galactic Plane (& Center) Mapping Issues
- Telescope Aperture
- Instrument Temperature

Orbit & Lifetime Issues

- Cryo missions and equatorial NEOs don't work
  - Sun, Earth avoidance "overconstrain" pointing
  - need dawn-dusk orbit
    - Sun-sync (evolving) - orbit "normal" to Earth-Sun line
    - Angular momentum conserving orbits hit Sun, Earth avoidance problems
    - both have Earth-eclipse "seasons"
- High orbits (>750km) can't be reached with Pegasus & M4

Galactic Plane (& Center) Mapping Issues

- Galactic Plane is almost perpendicular to ecliptic
- Sun-sync orbit sweeps through Galactic Center quickly
- For limited lifetime mission (<6 months) not all parts of sky can be viewed
- Launch date important
- Inclination important
- Eclipse season avoidance important
  - allows reducing battery mass, increasing launch mass margin
- Need the GI program to fully utilize the “other” part of the orbit not spent looking at the inner Galaxy

Telescope Aperture

- Larger is better for science
  - better angular resolution
  - smaller physical sizes probed
  - trace star formation on smaller scales -> better “Origins” connection
- Limited to 20cm in SMEX config
  - Pegasus shroud limits dewar size
  - Dewar limits telescope size
- Unlikely to change for M4/1999 SMEX
  - need smaller cryogen volume to expand aperture
  - cryocooler!

Instrument Temperature

- Detectors need to operate at 2K to be background limited
- Telescope needs to operate below 10K to keep instrument background limited
  - related to observing wavelength
    - shorter wavelengths can allow warmer telescope (they just won't sense any cool dust polarization)
- Superfluid Liquid Helium is the only acceptable cryogen
  - solid hydrogen (7-10K; WIRE) isn't cold enough for our detectors
  - hybrid cryostat (He for detector, H_2 for telescope) is EVEN more costly
  - M4 mission lifetime determined by Helium volume (110 liters) and heat load to cryogen

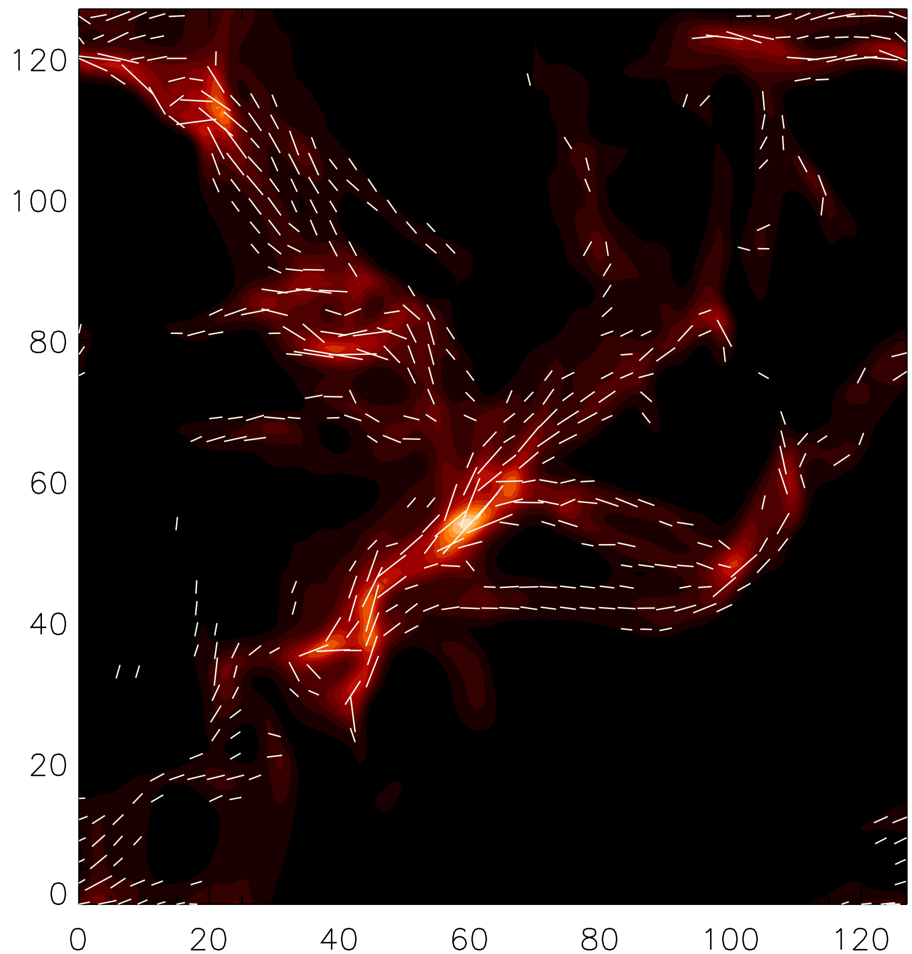
Why Cryocoolers Won’t Work

- 2-K space qualified cryocoolers are not yet available
- 10-K space qualified cryocoolers are not quite ready (Ball)
- Hybrid (2K dewar for detector; 10K cryocooler for telescope) is beyond SMEX cost range
  - but might enable a long duration MIDEX mission...

Warm Launch Won’t Work

- SIRTF-like configuration
  - detector cold at launch, telescope warm
  - on-orbit, telescope passively cools, then cryogen takes over
- M4 NEO won’t let telescope passively cool enough
- M4 can’t carry enough SFLHe to cool telescope and carry out mission

DUST EMISSION POLARIZATION MAPS:
WHAT CAN BE LEARNT FROM THE *M4* EXPERIMENT?



THE SCIENCE

The magnetic field plays an important role in the galaxy, especially in the processes of molecular cloud and star formation. However, to quantify the effect of the magnetic field in these fundamental processes, it is necessary to first discover its three dimensional structure and strength in the galaxy and in single clouds. Unfortunately, we still know very little about the field strength and spatial structure.

Polarization maps provide an excellent estimate of the orientation of the magnetic field on the plane of the sky, but do not measure the field strenth or the line of sight component of the field. How can M4 two dimensional maps tell us about the three dimensional field structure and strength, and shed new light on the problem of the origin of molecular clouds and stars?

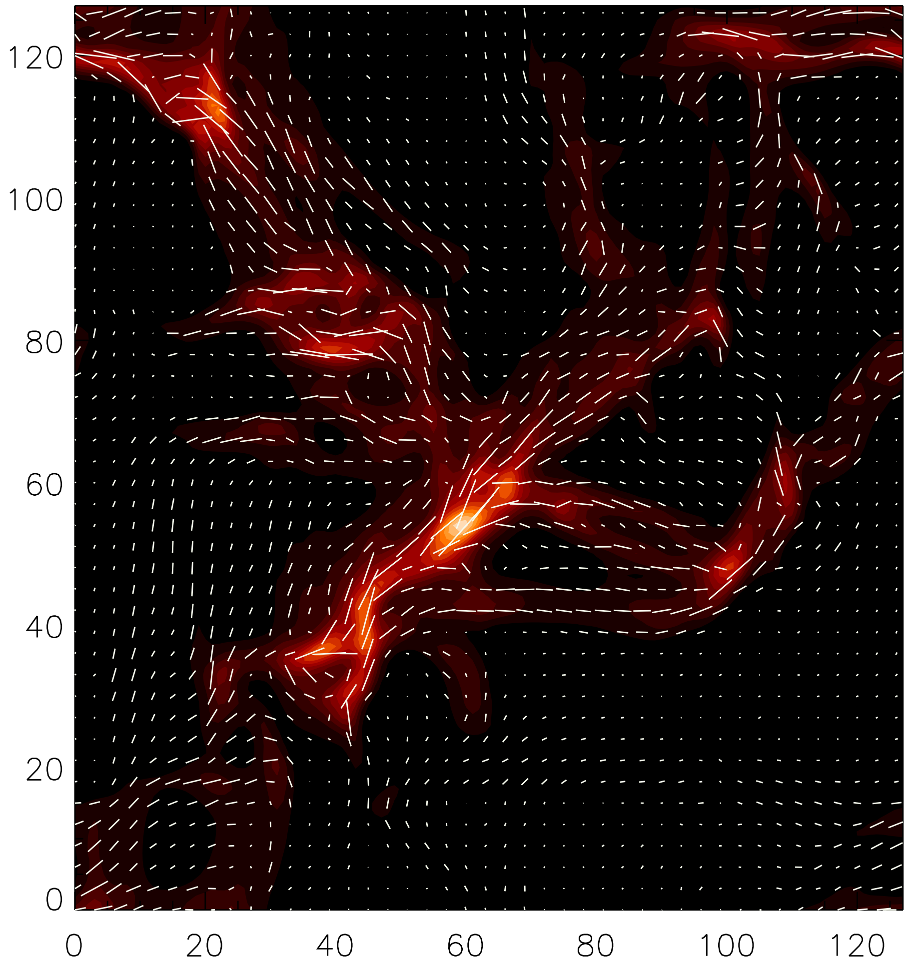
The answer relies on numerical simulations of magnetohydrodynamic (MHD) turbulence. Recent advances in numerical techniques and in computer performance have allowed the realization of large numerical experiments of MHD turbulent flows, in a regime that resembles the physical conditions in the interstellar medium (ISM). In these numerical experiments the most important parameter is the field stength (relative to the kinetic energy of the flow), that can be varied in order to study its effect.

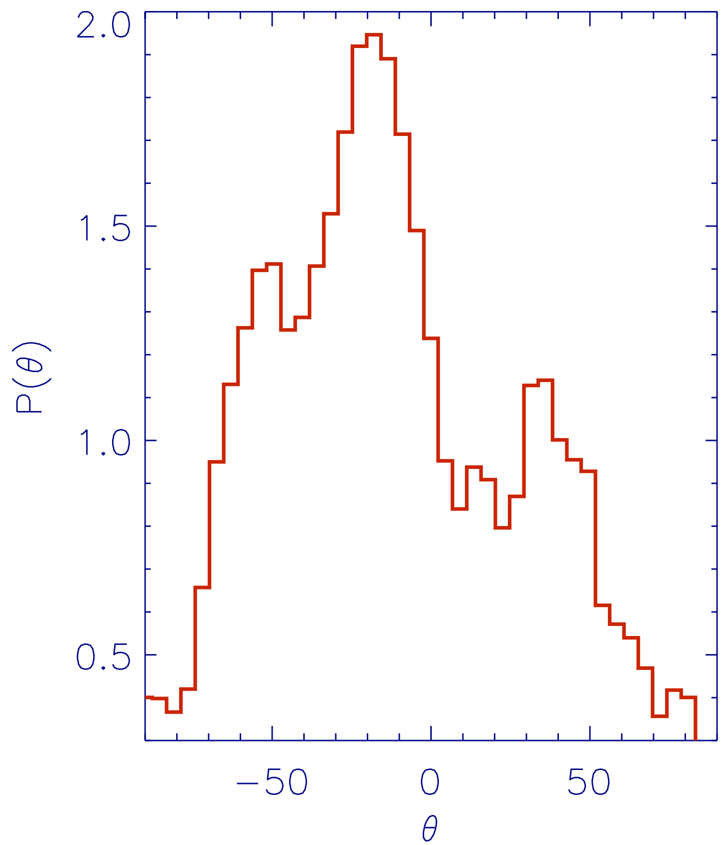
SYNTHETIC POLARIZATION MAPS

Synthetic polarization maps can be computed using the results of the MHD experiments (datacubes of density, velocity and magnetic fields), and can be compared with the observational maps obtained by *M4*.

Different statistics can be computed on the synthetic polarization maps, that are sensitive to the three dimensional structure and strength of the magnetic field. The same statistics can be computed on the observational polarization maps of *M4*, in order to extract the information about the three dimensional field strength and structure. The following are some of the statistical tools that are being developed for this purpose:

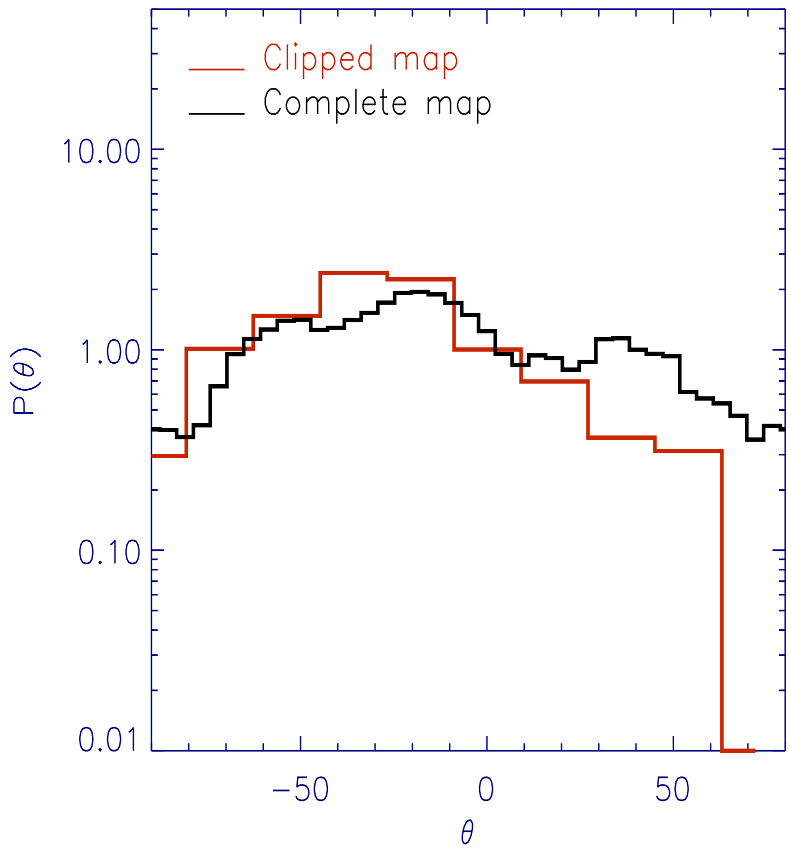
1) Histograms of polarization angle over a regularly sampled map:
Information on strength and direction



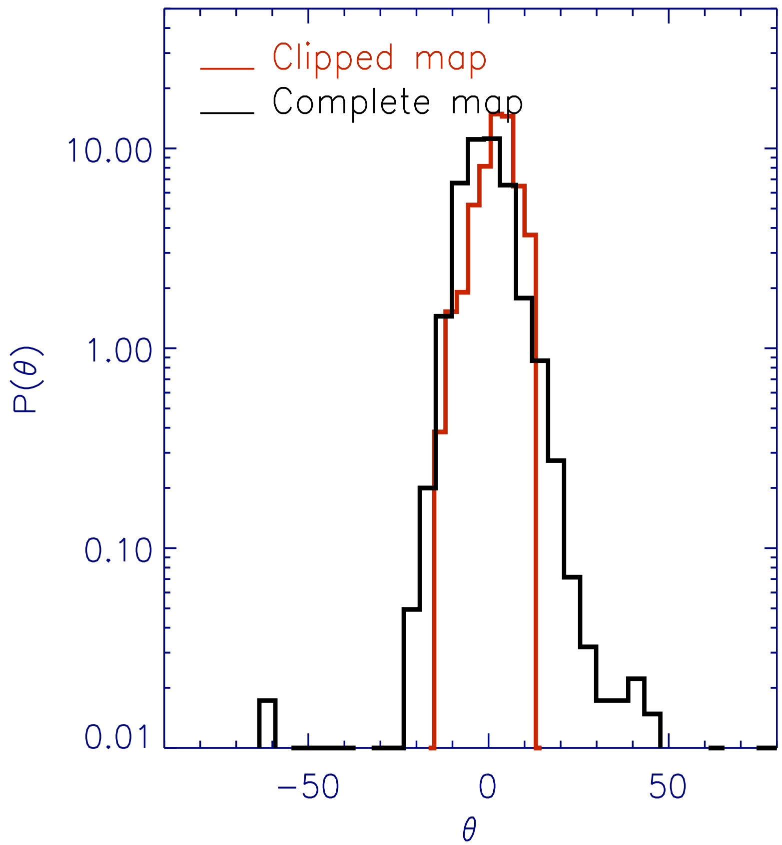


2) Histograms of polarization angle over a (clipped) map sampled only in regions of strong dust emission (eg filaments and cores) or regions of strong degree of polarization:
Information on strength and direction

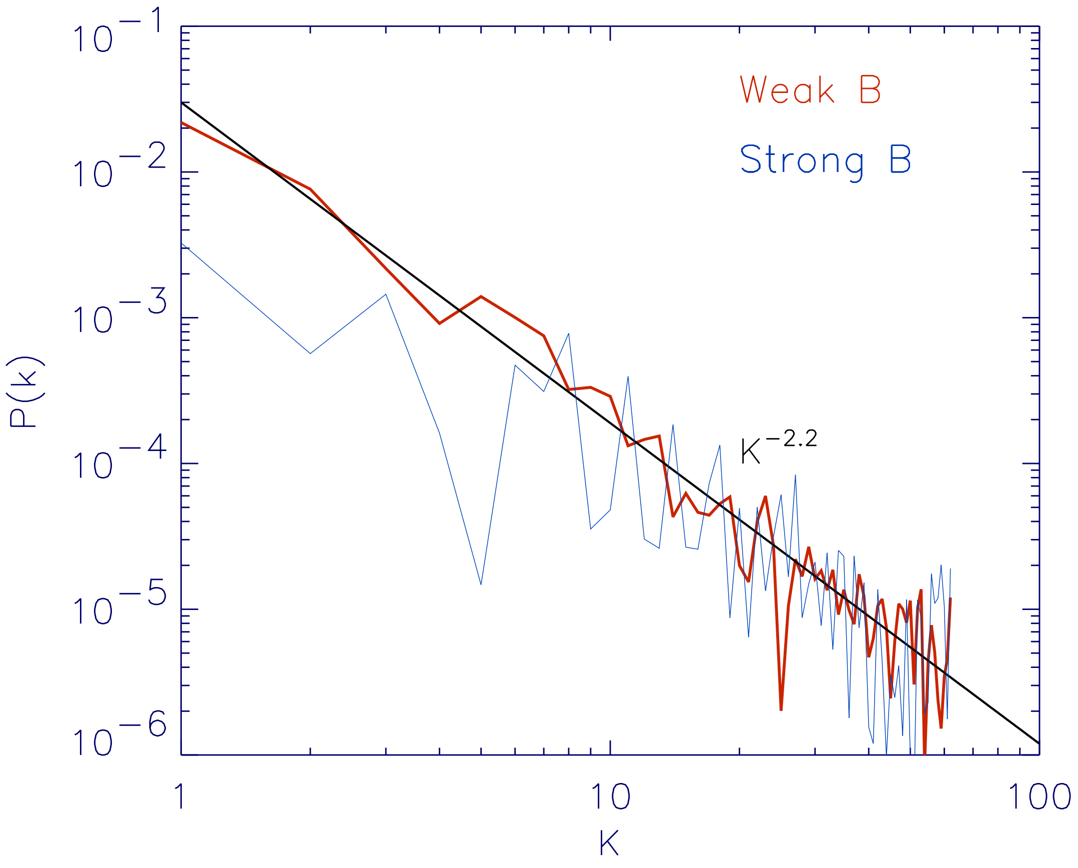
Weak B:



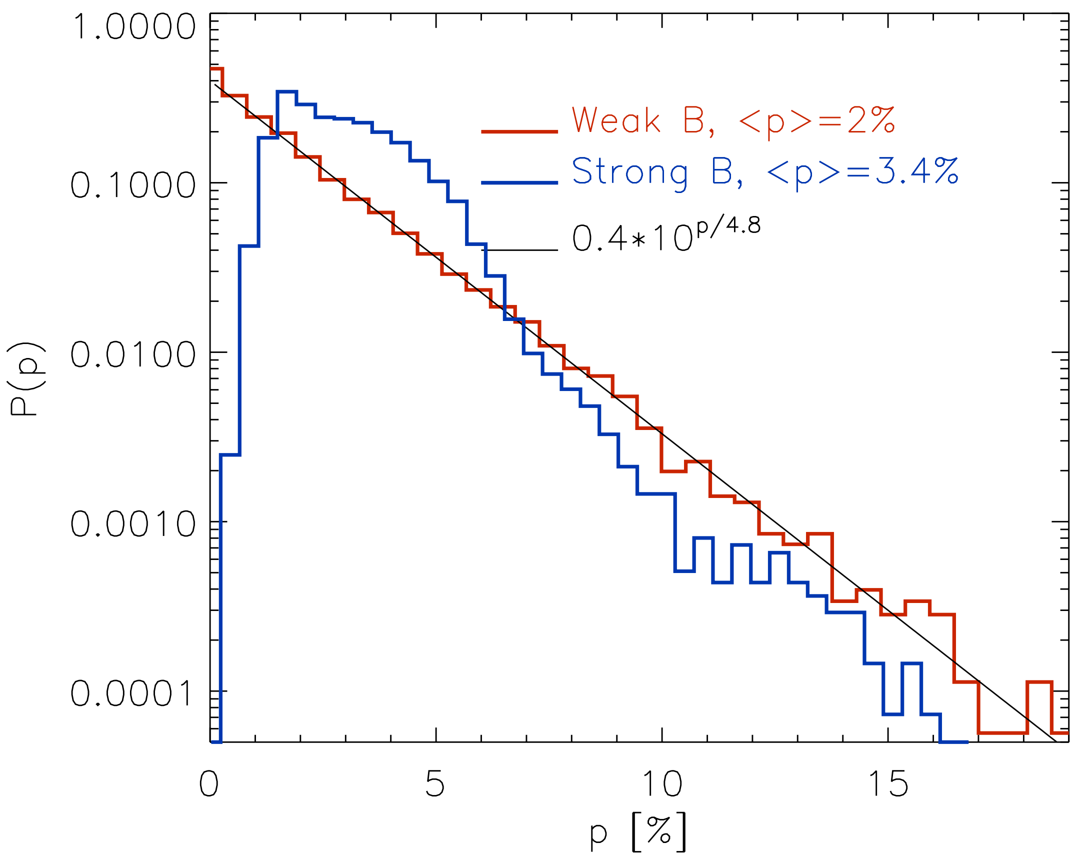
Strong B:



3) Power spectrum of polarization angle: Information on strength and direction

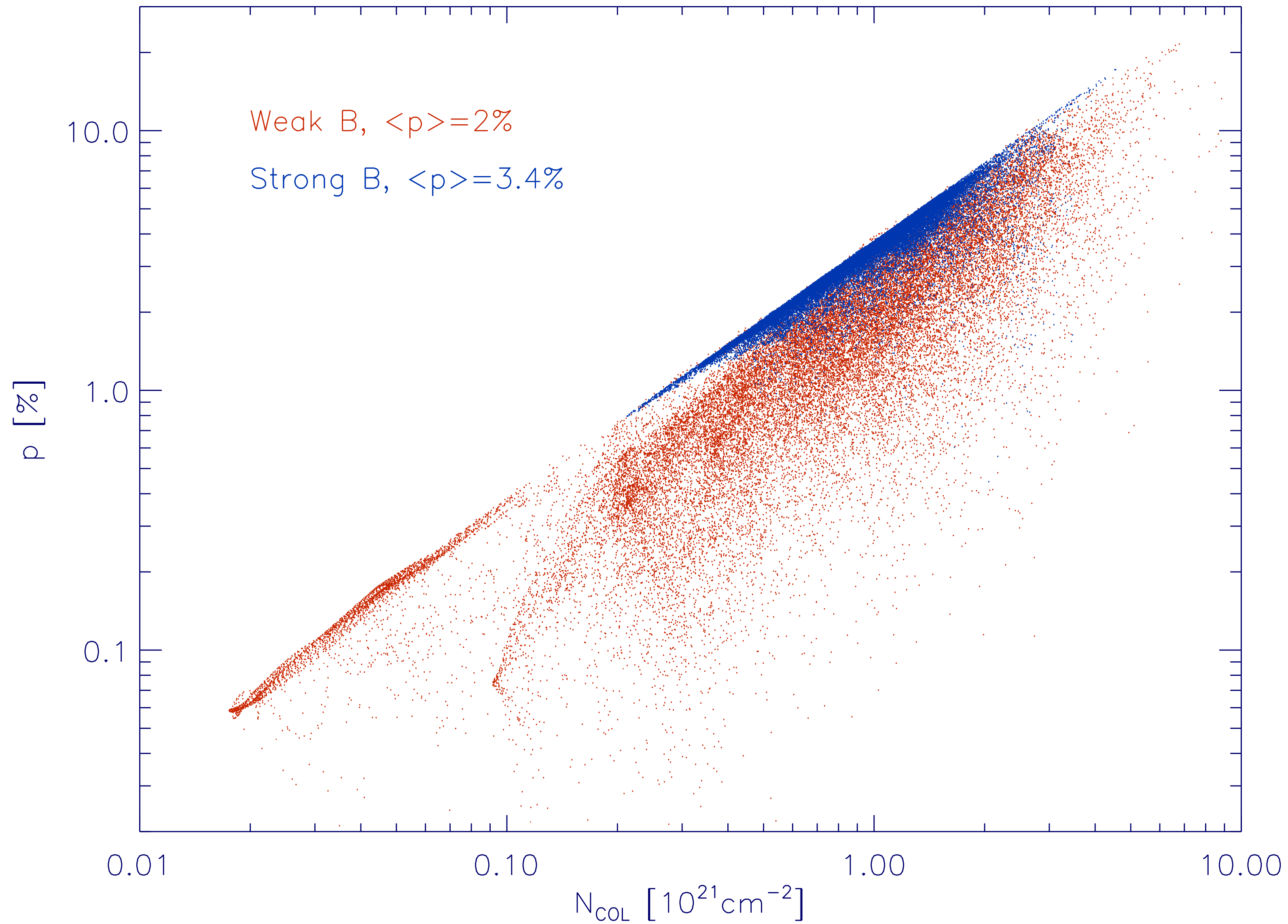


4) Histogram of degree of polarization: Information on strength and polarization efficiency



The histogram in the weak field case is a perfect exponential.

5) Degree of polarization versus dust emission: Information on strength, direction, and polarization efficiency



6) Histograms of angle between polarization vectors and major axis of filaments and cores: Information on strength