The 6th *Solar-B* Science Meeting

Flare-associated shock waves observed in soft X-ray

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Outline

1. flare-associated shock wave
2. propagation of shock wave
    1. *Yohkoh*/SXT (previous work)
    2. *Solar-B*/XRT (observational plan)
3. origin of shock wave (SOT)
4. conclusion
5. Appendix

1

flare-associated shock wave

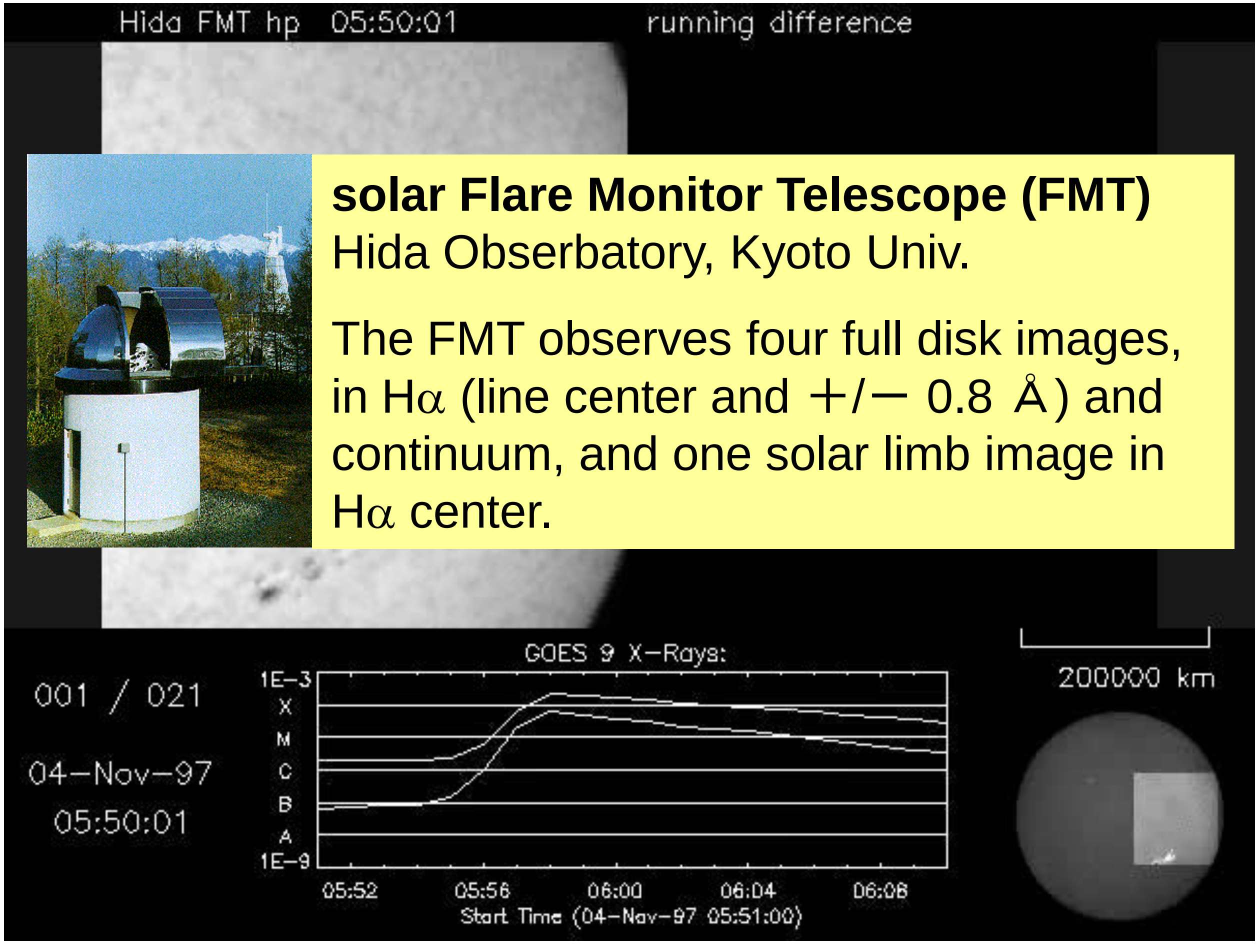
1

Flare-associated waves

Moreton wave	Hα Hida/FMT etc. Chromospheric	discovered by Moreton (1960) identified by Uchida (1968)
EIT wave	EUV *SOHO*/EIT coronal	Thompson et al., 1999 Klassen et al., 2000 Biesecker et al., 2002
X-ray wave	soft X-ray *Yohkoh*/SXT coronal	Khan and Hudson, 2000 Khan and Aurass, 2001 Narukage et al., 2002 Hudson, 2003 Narukage et al., 2004
He wave	He I transition region	Vrsnak et al., 2002

1 Moreton wave 1997/11/04

Eto et al., 2002



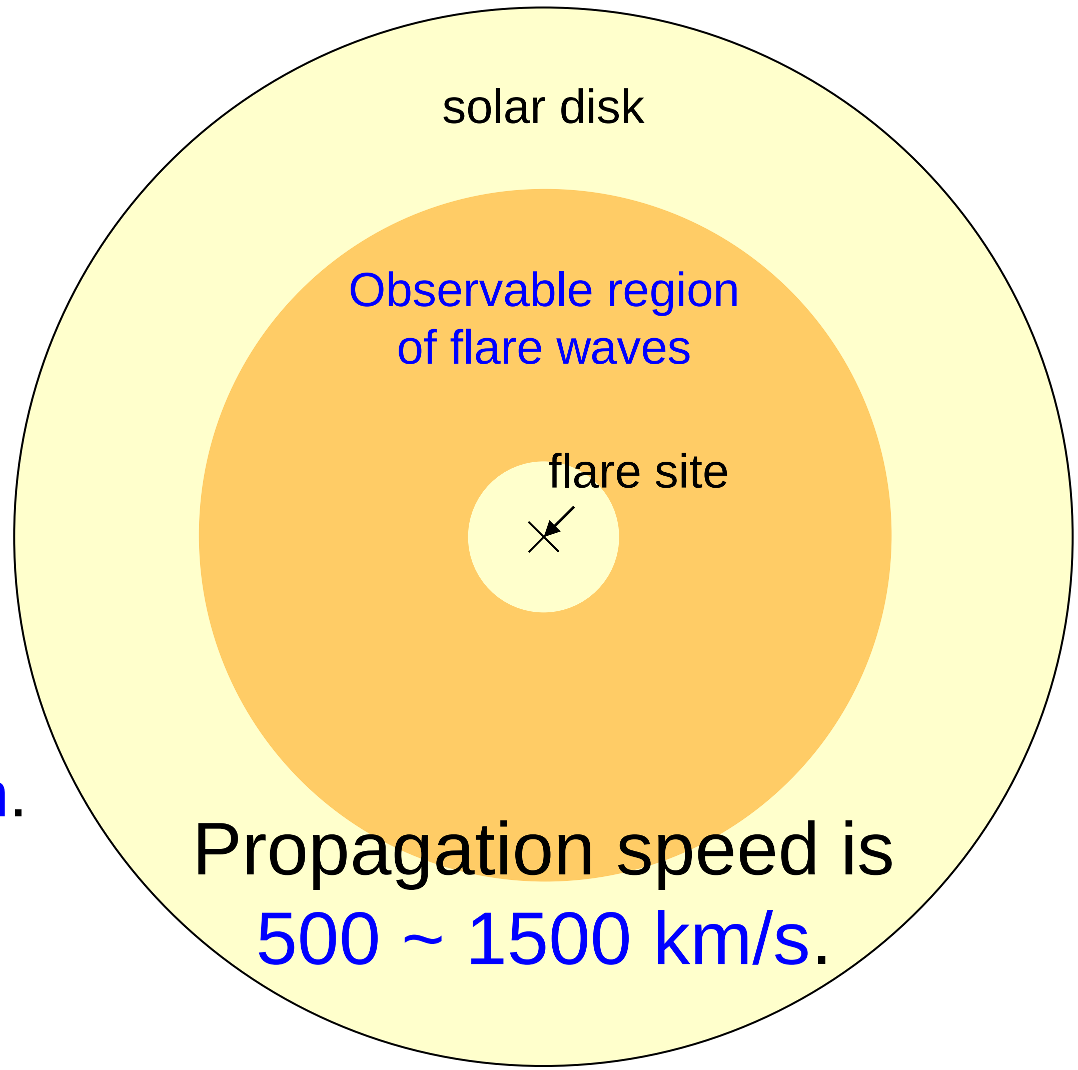
solar Flare Monitor Telescope (FMT)
Hida Obserbatory, Kyoto Univ.

The FMT observes four full disk images, in Hα (line center and +/− 0.8 Å) and continuum, and one solar limb image in Hα center.

1 Observable region of flare waves

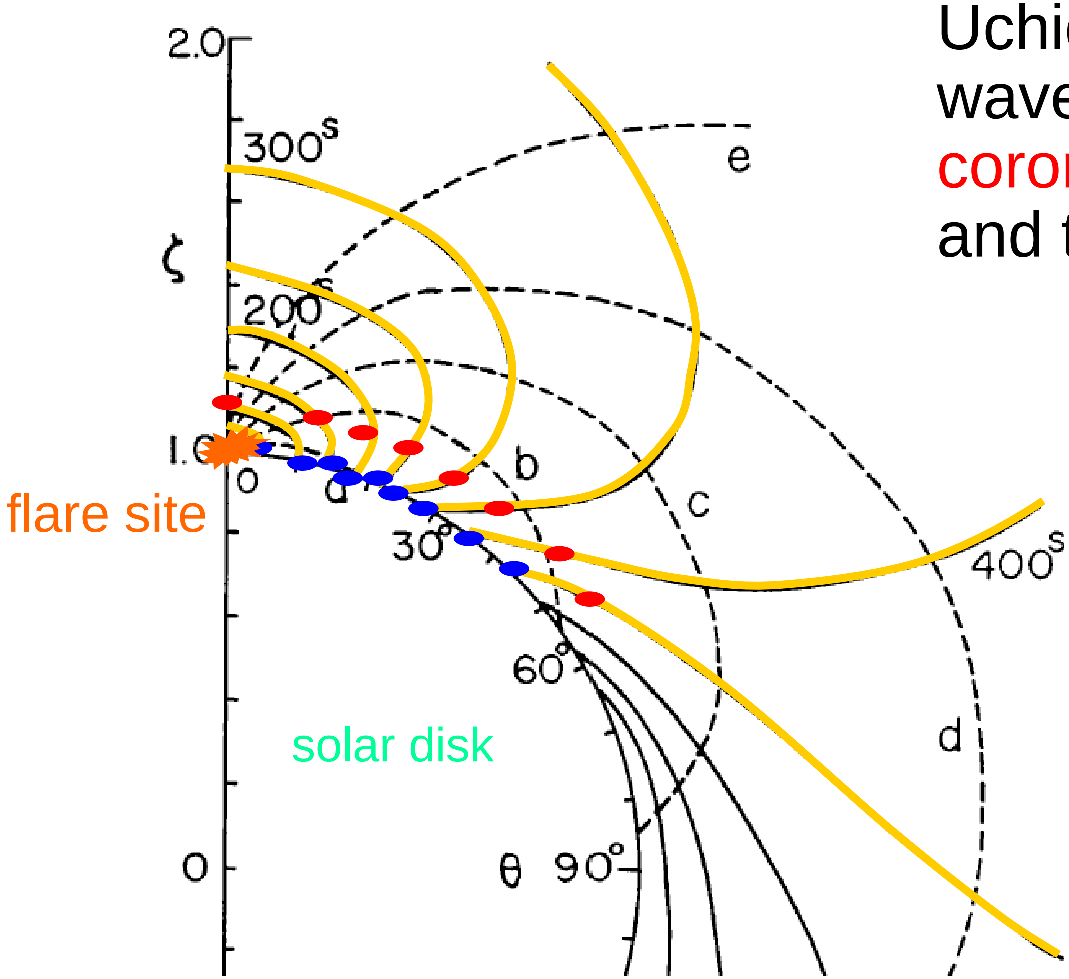
Moreton wave & X-ray wave

- Flare waves usually become visible only at a distance of more than 100,000 km from the flare site.
- Some flare waves can propagate up to distance exceeding 500,000 km.



Propagation speed is
500 ~ 1500 km/s.

Uchida model (1968)



Uchida identified the Moreton wave as the intersections of a coronal MHD fast shock front and the chromosphere.

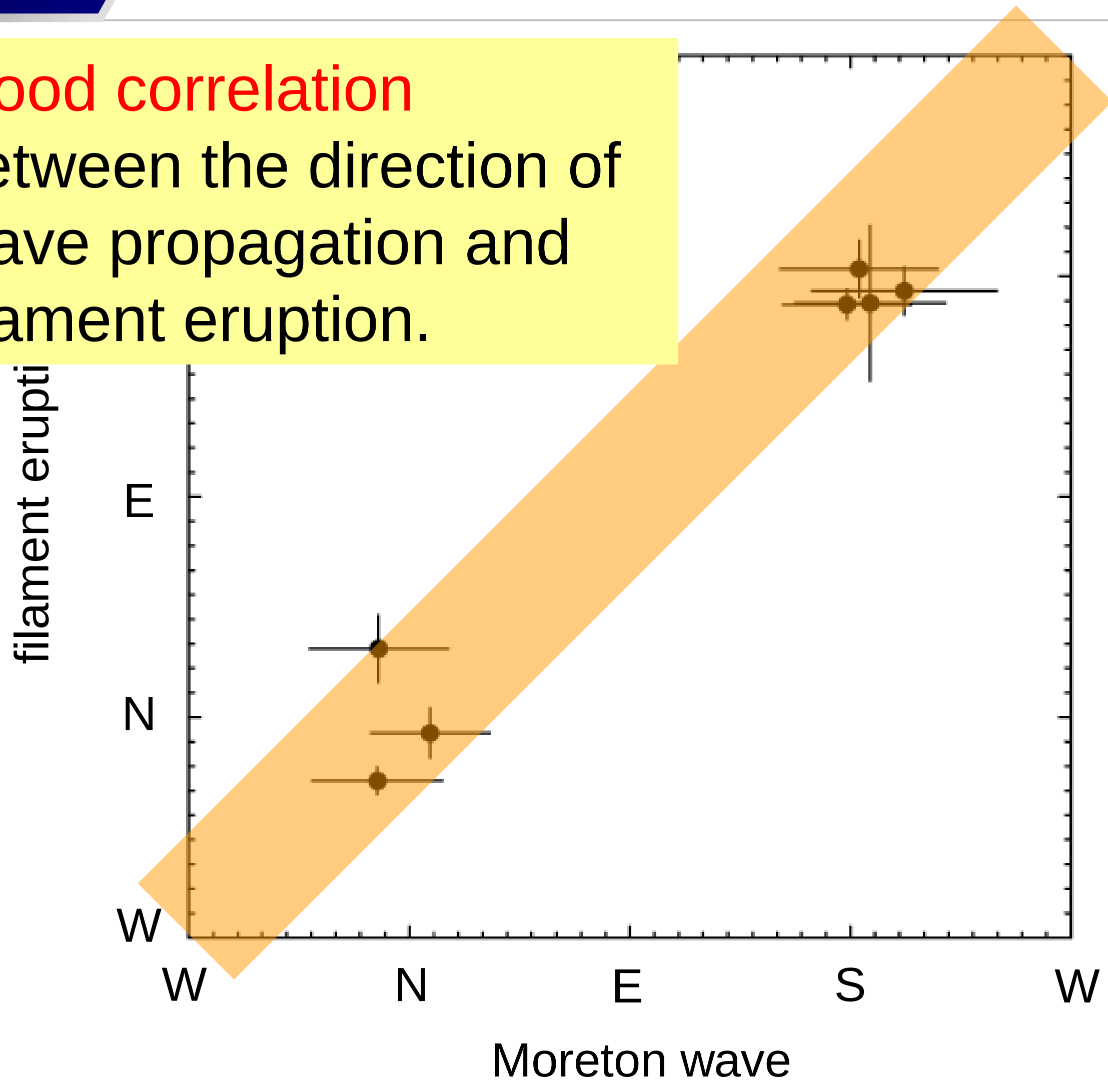
shock front

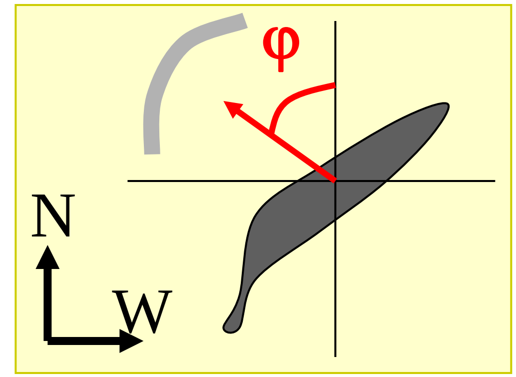
Moreton wave

X-ray wave,
coronal counterpart of Moreton wave

1 Moreton wave and filament eruption

Good correlation between the direction of wave propagation and filament eruption.

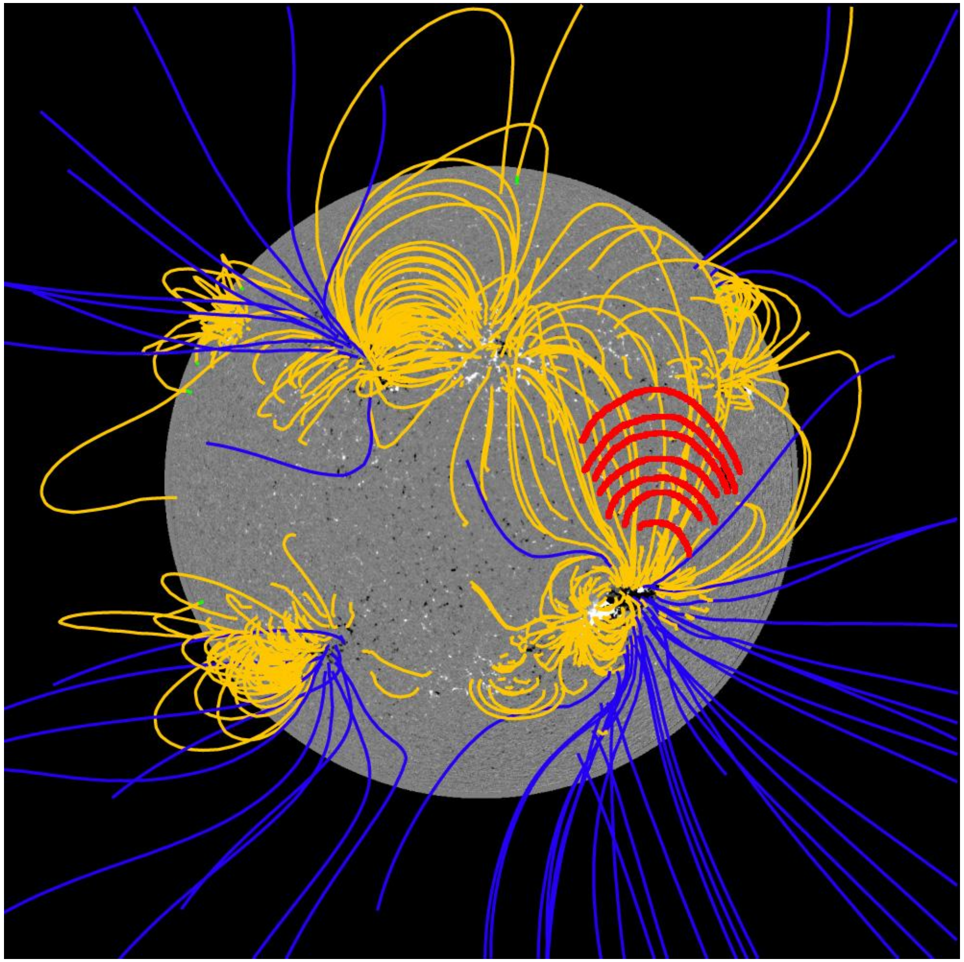




In all Moreton wave events, filament eruptions were observed.

Magnetic fields

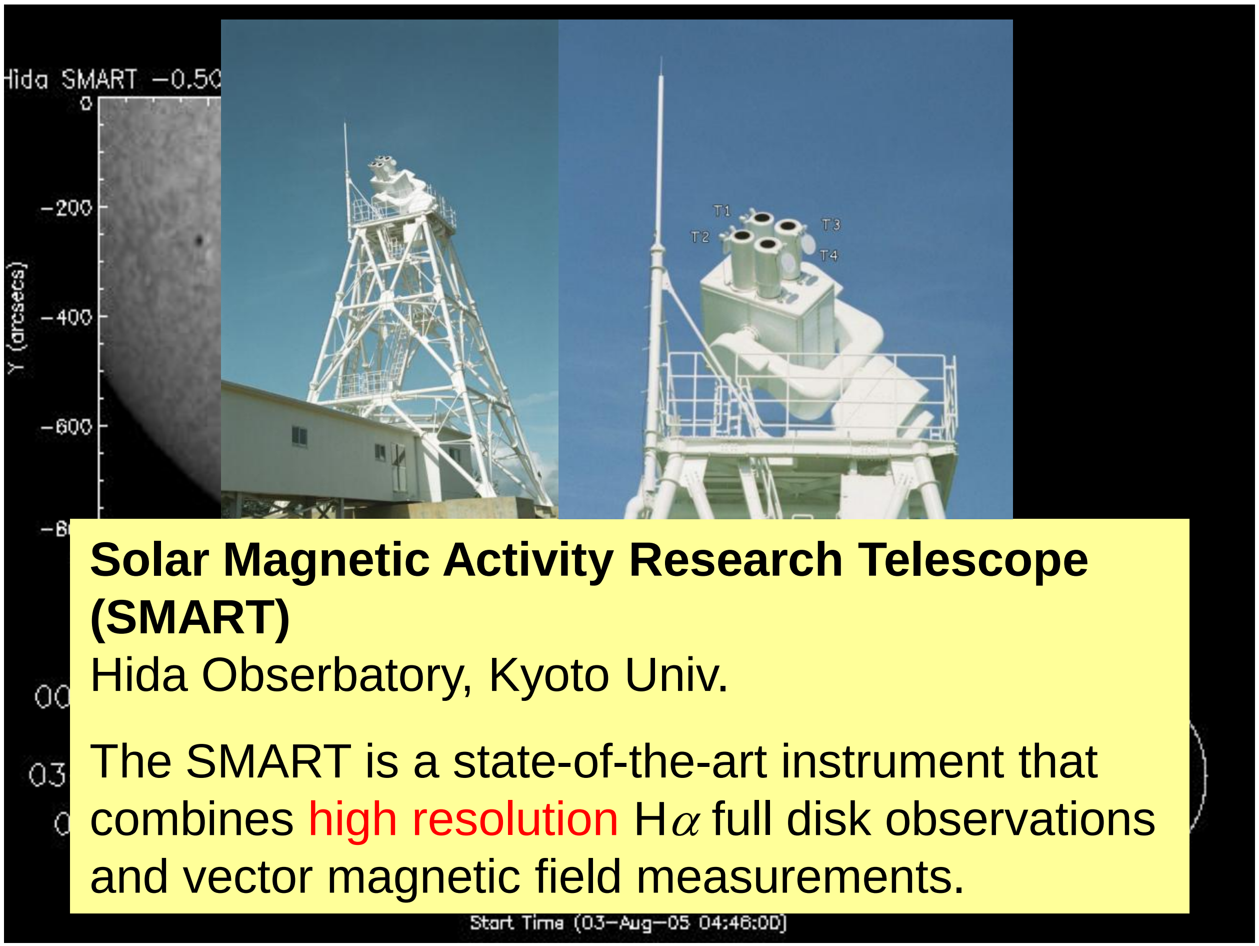
1997/11/04



- Moreton waves tend to propagate along the global magnetic fields.

1 Double shock generation

High-resoluble observation of Moreton wave with Hida/SMART

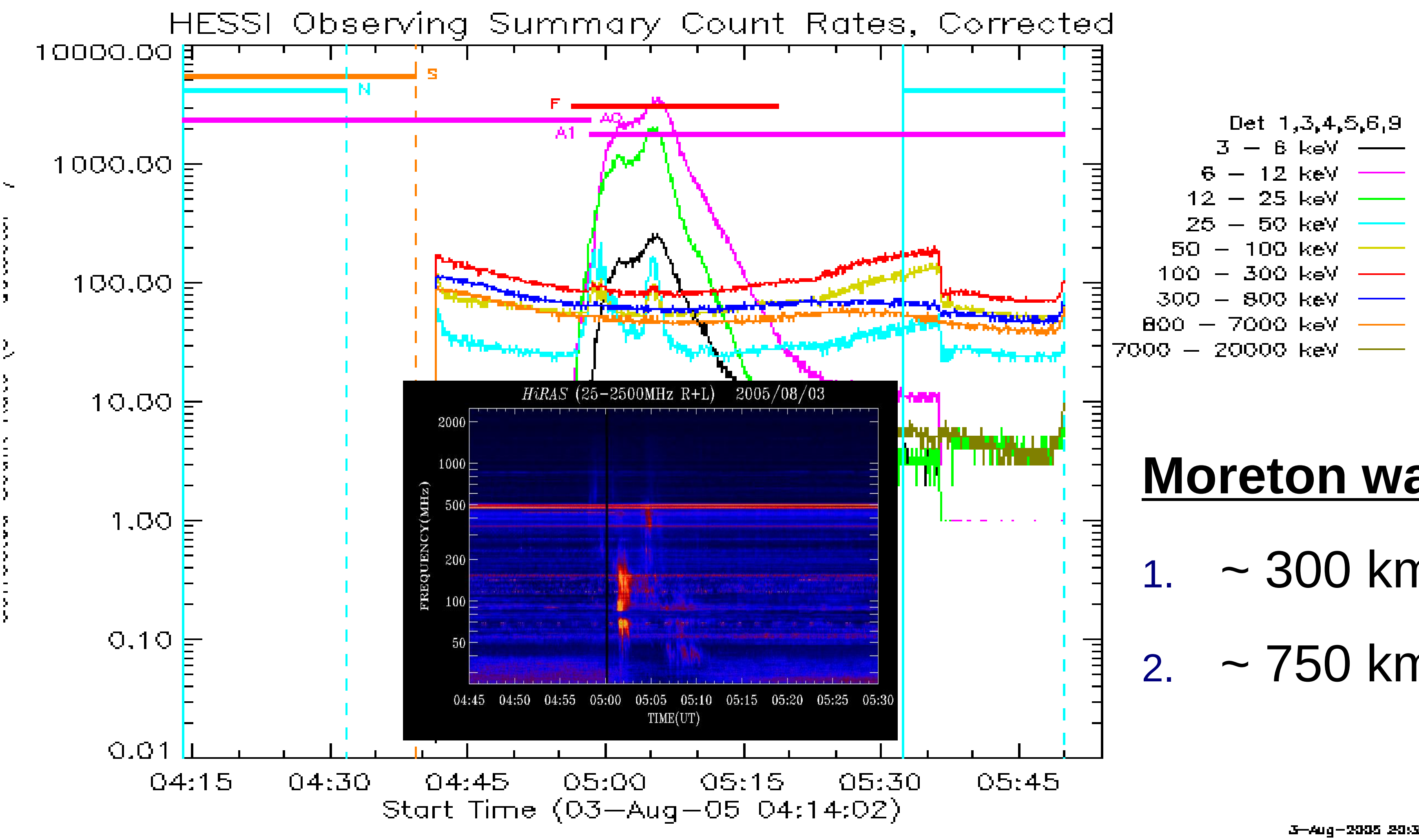


Solar Magnetic Activity Research Telescope (SMART)
Hida Obserbatory, Kyoto Univ.

The SMART is a state-of-the-art instrument that combines high resolution Hα full disk observations and vector magnetic field measurements.

1 Double shock generation

Moreton waves, RHESSI & type II radio burst

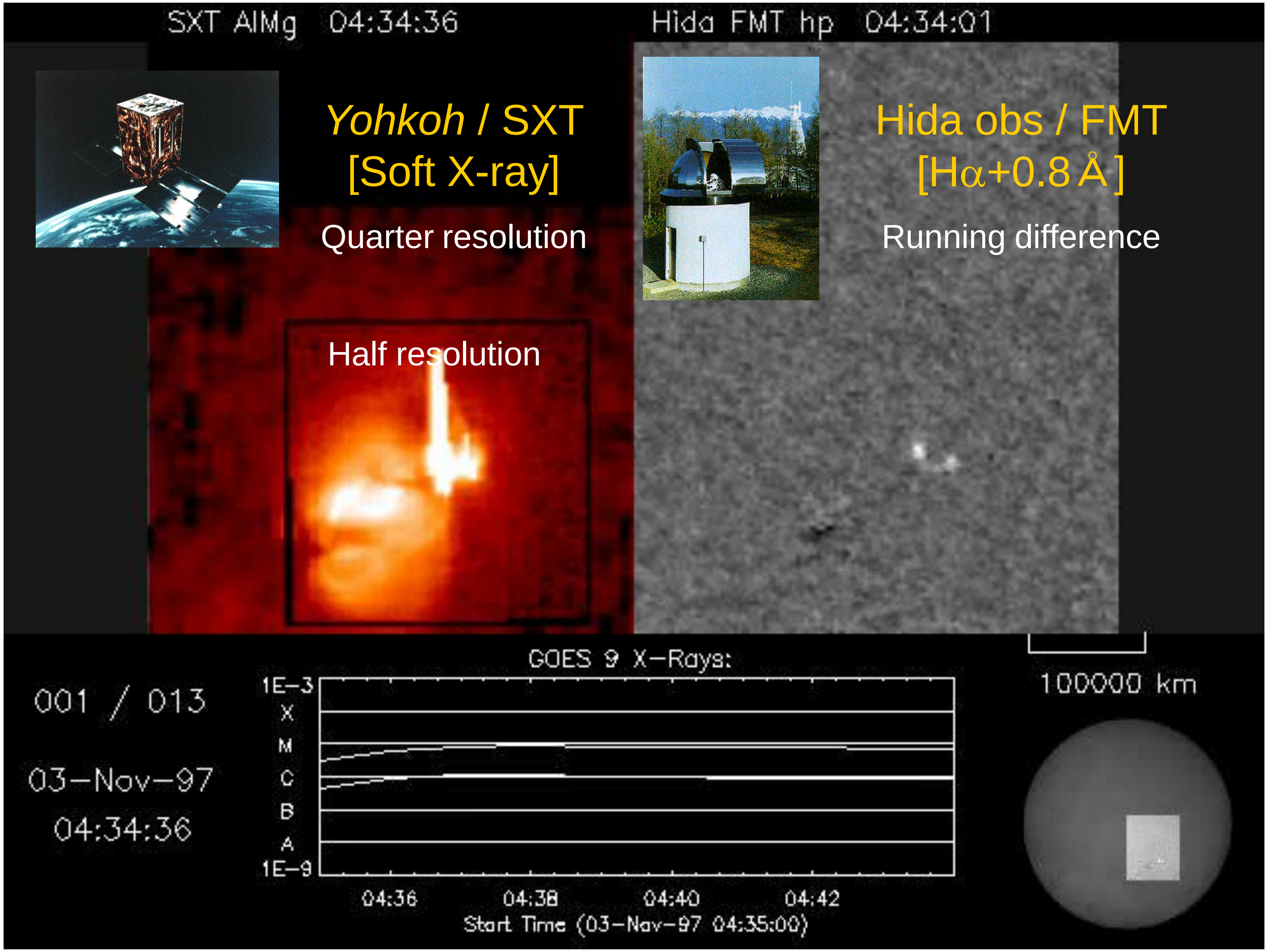


Moreton wave

1. ~ 300 km/s
2. ~ 750 km/s

1 X-ray wave 1997/11/03

Narukage et al., 2002



1 Study of shock wave

Question

- How is the shock wave generated?
  - key : filament eruption, magnetic field in flare region
- How does the shock wave propagate?
  - key : global magnetic field
  - application : coronal seismology
- How much energy does spend on the shock generation and propagation?

➔ The shock observation in X-ray is indispensable, because we need the physical quantities.

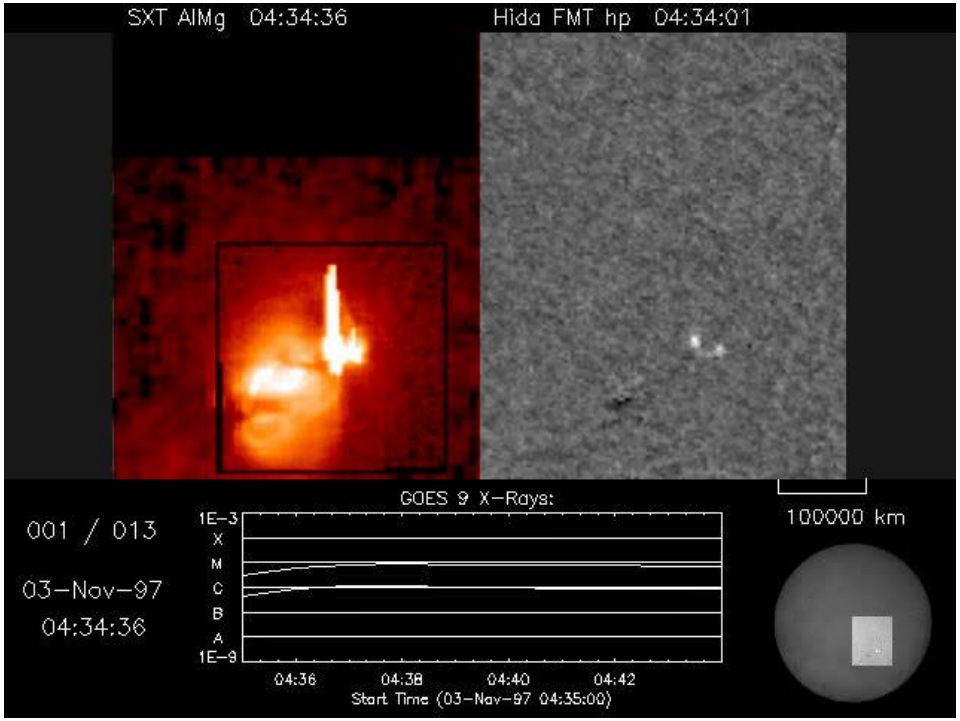
2

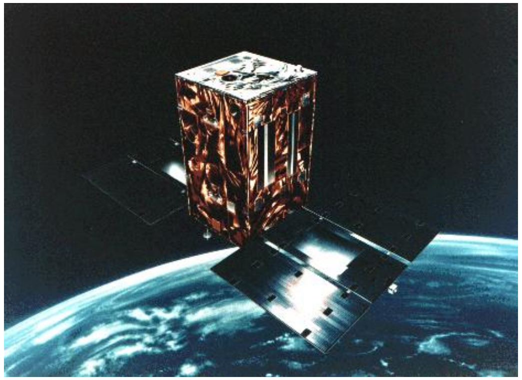
propagation of shock wave

1. *Yohkoh*/SXT (previous work)

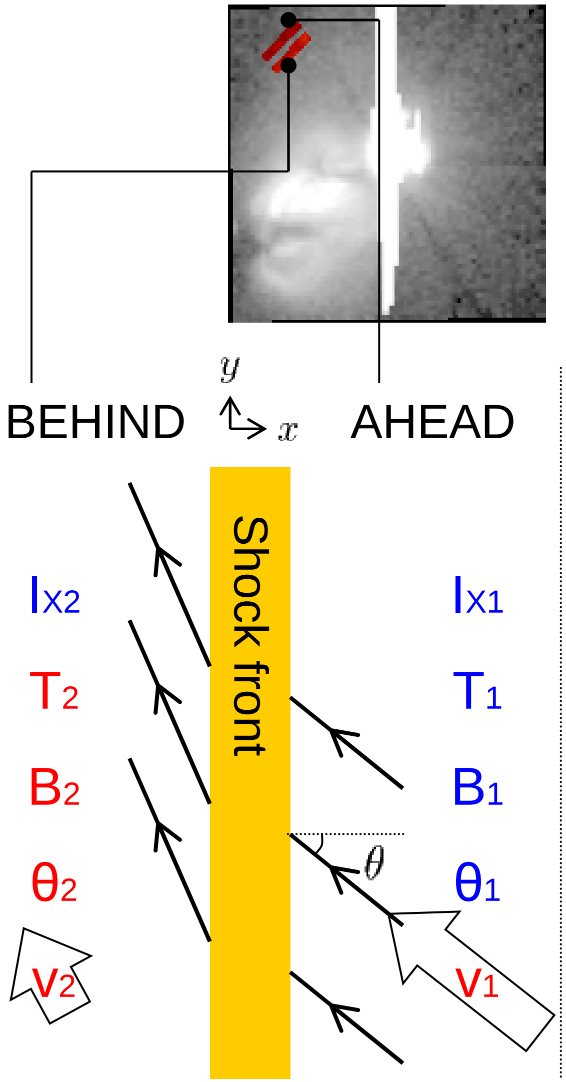
2.1 Advantage of *Yohkoh* / SXT

Using *Yohkoh* / SXT images,
we can estimate the quantities of the X-ray wave.





2.1 Is the X-ray wave a MHD fast shock?



$$X \equiv \frac{\rho_2}{\rho_1}, \tag{1}$$

$$\left(v_1^2 - X v_{A1}^2\right)^2 \left\{X c_{s1}^2 + \frac{1}{2} v_1^2 \cos^2\theta_1 (X(\gamma-1) - (\gamma+1))\right\} + \frac{1}{2} v_{A1}^2 v_1^2 \sin^2\theta_1 X \left\{(\gamma + X(2-\gamma)) v_1^2 - X v_{A1}^2((\gamma+1) - X(\gamma-1))\right\} = 0, \tag{2}$$

$$\frac{v_{2x}}{v_{1x}} = X^{-1}, \tag{3}$$

$$\frac{v_{2y}}{v_{1y}} = \frac{v_1^2 - v_{A1}^2}{v_1^2 - X v_{A1}^2}, \tag{4}$$

$$\frac{p_2}{p_1} = X + \frac{(\gamma-1) X v_1^2}{2 c_{s1}^2} \left(1 - \frac{v_2^2}{v_1^2}\right), \tag{5}$$

$$\frac{T_2}{T_1} = \frac{p_2/p_1}{\rho_2/\rho_1} = \frac{p_2/p_1}{X}. \tag{6}$$

$$I_X = n^2 V f(T) \propto \rho^2 f(T), \tag{7}$$

Using MHD Eq. (1)-(7), the observable quantities (I_{X1},I_{X2},T_1,B_1,θ_1) by *Yohkoh*/SXT determine (v_1,T_2,B_2,θ_2,v_2).

2.1 Is the X-ray wave a MHD fast shock?

Using this method,

we can estimate the quantities of the X-ray wave.

e.g.

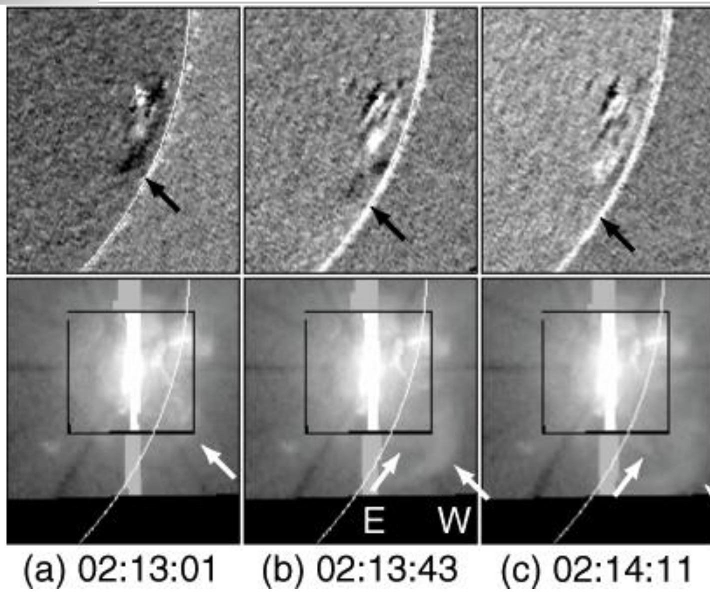
The estimated fast shock speed (v_1) is 400 ~ 760 km/s, which is roughly agreement with the observed propagation speed of the X-ray wave, 630 km/s.

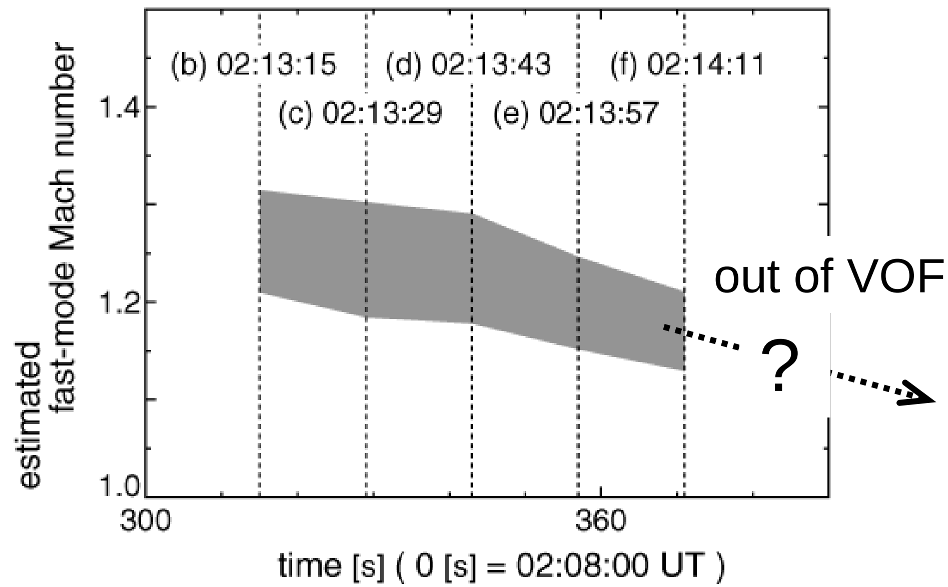
The fast mode Mach number is 1.15 ~ 1.25.

These results suggest that the X-ray wave is an MHD fast shock propagating through the corona and hence is the coronal counterpart of the Moreton wave.

Narukage et al. 2002, ApJ Letters 572, 109

2.1 estimates Mach number





X-ray wave observed on 2000/03/03,

- The fast mode Mach number decreased.
- The timing when the Mach number become “1” consists with the disappearance of the Moreton wave.

➔ We need more example!

Narukage et al. 2004, PASJ, 56, L5

2

propagation of shock wave

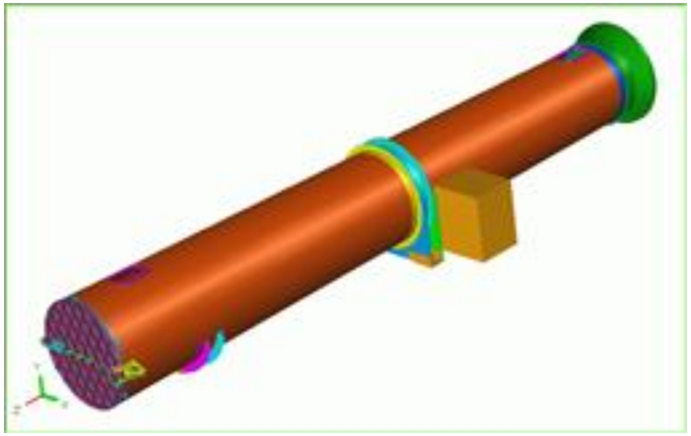
2. *Solar-B*/XRT

2.2 Solar-B

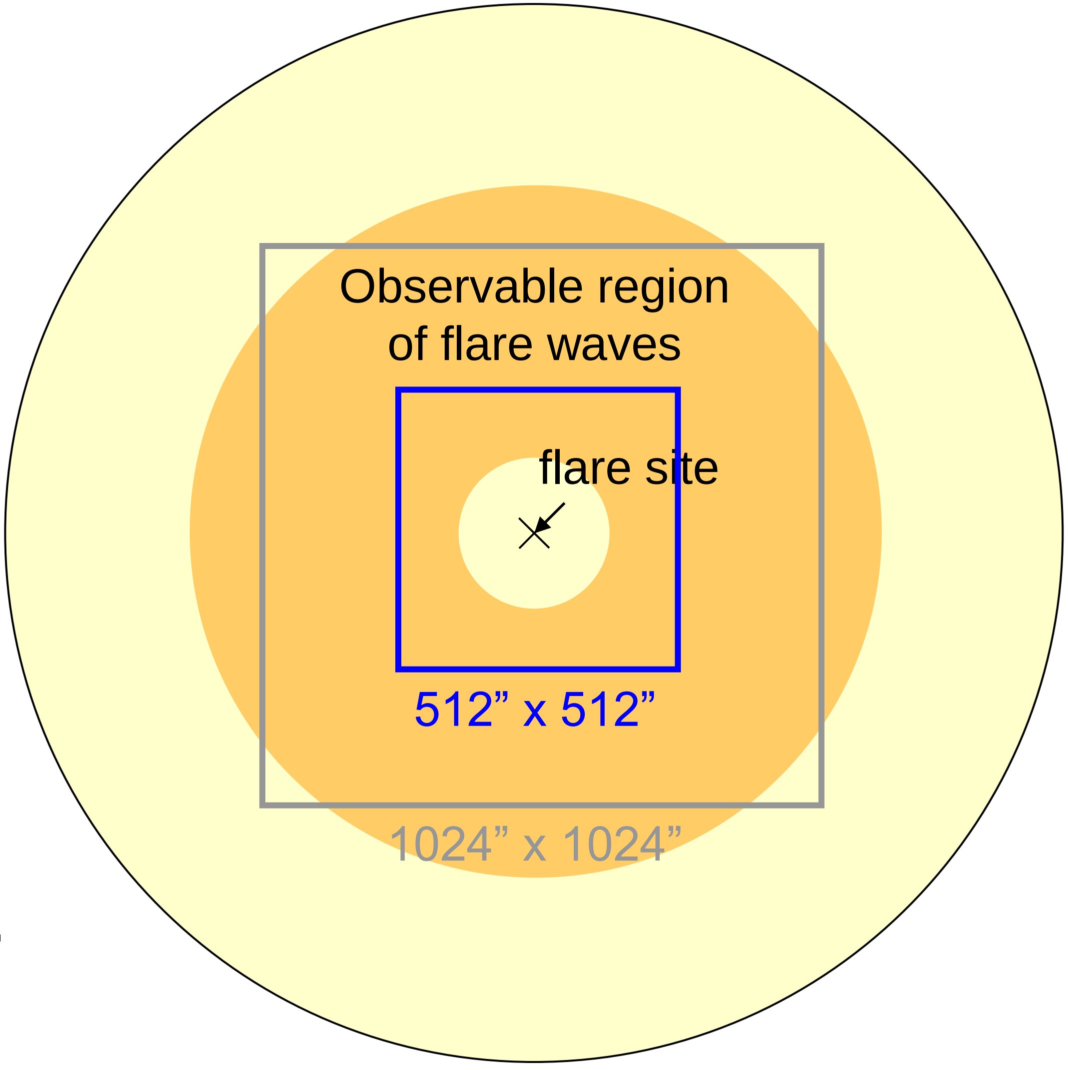
Using this method, we can examine
the possibility of wave detection with XRT
and suggest the observational plan.

2.2 XRT – field of view

X-Ray Telescope



- **<u>Field of view</u>**
  The observations of X-ray waves require the field of view as larger than 512” x 512”.

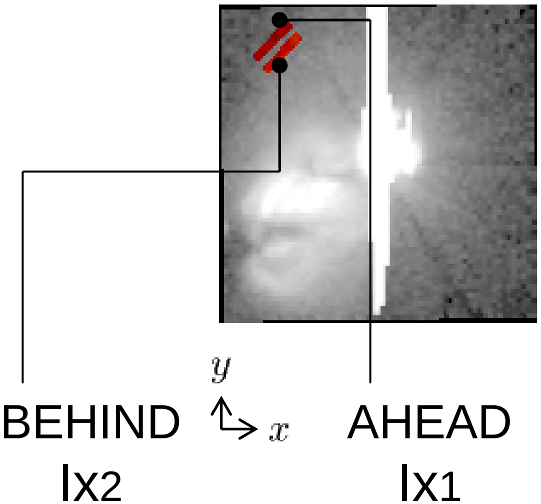


2.2 XRT – cadence & pixel size

X-Ray Telescope

- **Pixel size**
  The thickness of the wave is about 40,000 km.

  → The pixel size should be smaller than 4” x 4”.



- **Time cadence**
  The propagation speeds of X-ray wave are 500 ~ 1500 km/s.

  → We can observe for less than 270 ~ 800 sec.
  The observation needs as high cadence as possible.

The FOV, pixel size and time cadence are depend on the data recorder capacity (15% of 8Gbits = 1.2Gbits = 150Mb).

2.2 XRT – filter

X-Ray Telescope

- **Filter selection**
  XRT has 9 filters.

  We need 2 filters to estimate the plasma temperature and emission measure.

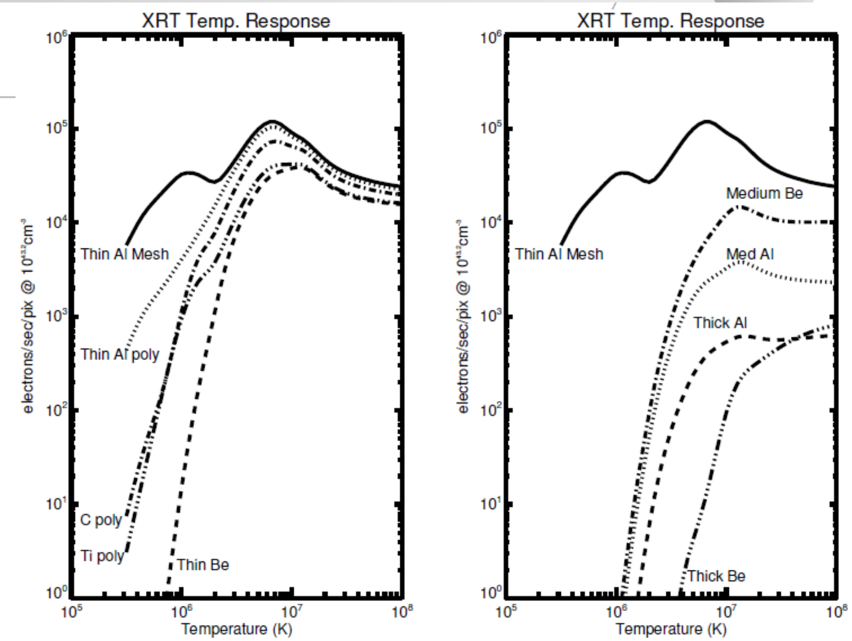


Table 2. Design of X-ray analysis filters

Name	Metal		Substrate
Thin-Al/Mesh	Al	1600 Å	Mesh
Thin-Al/Poly	Al	1250 Å	Polyimide 2500 Å
C/Poly	C	4800 Å	Polyimide 2500 Å
Ti/Poly	Ti	2300 Å	Polyimide 2500 Å
Thin-Be	Be	9 μm	Mesh
Med-Be	Be	30 μm	—
Med-Al	Al	12.5 μm	—
Thick-Al	Al	25 μm	—
Thick-Be	Be	1 mm	—

2.2 XRT – filter selection

T (MK)	2.25 → 2.78		
em (cm^{-5})	$10^{27.0}$ → $10^{27.3}$		
n (cm^{-3})	$10^{8.5}$ → $10^{8.6}$ (X=1.30)		
[DN sec^{-1} arcsec^{-2}]	***Ix1***	***Ix2***	***Ix2 / Ix1***
Entrance	280	578	2.06
Thin Al Mesh	191	444	2.33
Thin Al poly	130	347	2.68
C poly	71	205	**2.91**
Ti poly	36	101	**2.83**
Thin Be	14	58	**4.16**
Medium Be	1	6	**4.61**
Medium Al	1	3	**4.50**
Thick Al	0	0	--
Thick Be	0	0	--

I calculate the XRT intensities (Ix1 and Ix2) and their ratios, using my result of *Yohkoh* X-ray wave.

To recognize the shock against the background, the intensity ratio (=I_{x2} / I_{x1}) should be larger than 3.

2.2 XRT – filter selection

X-Ray Telescope

- I examine the enough ***exposure time*** (t) to suppress the effect of photon noise σ.

σ [DN] = $N^{1/2}$ [p] * 300 (conversion factor) [e^-/p] / 57 [e^-/ DN]

$(Ix2 - Ix1)\ t > 3\sigma(t)$

Note : photon noise is superior to the other noise.

- Photon noise = $N^{1/2}$ * 300e^-
- System noise < 30e^-
- Dark = 0.1e^- / sec / pix

➔ I select the suitable filters for X-ray waves.

2.2 XRT – filter selection

pixel size	1” x 1”	2” x 2”	4” x 4”	minimum FOV = 512” x 512”
minimum image size	512 x 512	256 x 256	128 x 128	
	minimum exposure time [msec]			Ix_2 / Ix_1
C poly	378	95	24	2.91
Ti poly	845	211	53	2.83
Thin Be	418	105	26	4.16
Medium Be	2411	603	151	4.61
Medium Al	4541	1135	284	4.50

note : The influence of flare-loop brightness is not considered.

2.2 XRT – filter selection

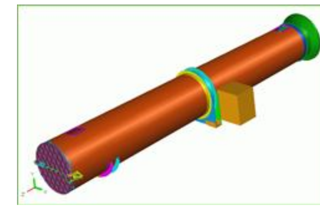
pixel size	1” x 1”	2” x 2”	4” x 4”
	DN of **Ix1 / Ix2 / AR** at a exposure time of **250 msec**		
C poly	18 / 51 / 1218	**71 / 205 / 4872**	282 / 821 / sat.
Ti poly	9 / 25 / 601	**36 / 101 / 2404**	143 / 405 / sat.
Thin Be	3 / 15 / 327	14 / 58 / 1308	56 / 233 / sat.

Table 4. Typical count rate (unit : DN/pixel)

Exposure	Quiet Sun		AR(no High)		AR(+High)		Flare(M2)	
[sec]	32.0	11.3	1.41	0.250	0.500	0.032	0.004	0.001
Thin-Al/Mesh	sat.	1841	sat.	3777	sat.	3021	sat.	sat.
Thin-Al/Poly	943	333	sat.	2099	sat.	2570	sat.	sat.
C/Poly	368	130	sat.	1218	sat.	1817	sat.	sat.
Ti/Poly	217	77	3392	601	sat.	1017	sat.	sat.
Thin-Be	46	16	1843	327	sat.	835	sat.	sat.
Med-Be	5	2	222	39	3023	193	sat.	3400
Med-Al	2	1	109	19	997	64	3691	923

2.2 XRT – observational plan

X-Ray Telescope



- We suppose the **shock observation mode**.

Following plan is a minimum-data-size plan.

	selection	note
filters	*C poly* & *Ti poly* set	Wave & AR are not saturated.
exposure time	125 msec	
pixel size	2” x 2”	768” x 768” FOV 144 k pixel data size : 1728 kbits / image
image size	384 pixel x 384 pixel	
compression	loss less	50% → 864 kb / image
time cadence	15 sec	10 k pixel / sec 60 images (30 filter sets) = 50.6Mbits (4% of 1.2Gbits)
obs. time	900 sec	

2.2 XRT – observational plan

X-Ray Telescope

- In the X-ray waves observed with *Yohkoh*/SXT, it is difficult to identify the shock waves only with the X-ray observations.

➔ The simultaneous observation with the ground instruments is required.

➔ The plasma velocity derived with *Solar-B*/EIS is also important.

Hα	Moreton wave
Radio spectrum	metric type II radio burst
Solar-B/EIS	plasma velocity

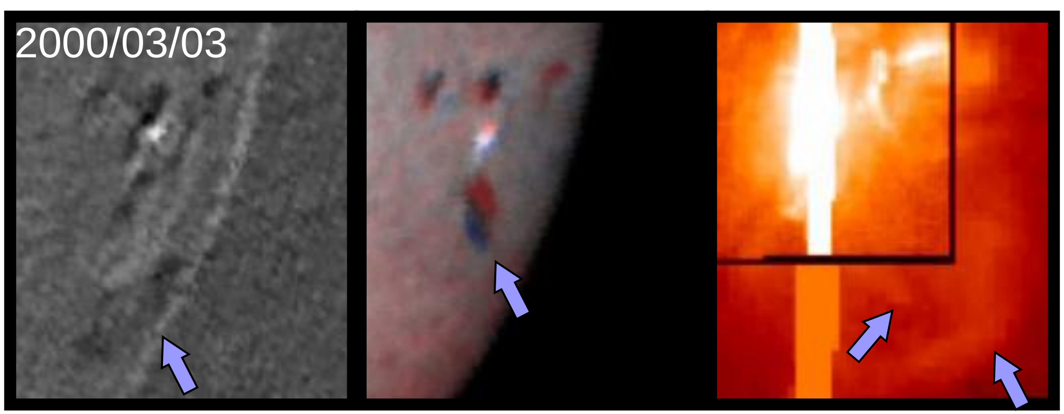
3 origin of shock wave

Solar-B/SOT

3 origin of Moreton wave

- In all Moreton wave events, filament eruptions were observed.
- In some cases of X-ray waves, X-ray ejecta were also observed.

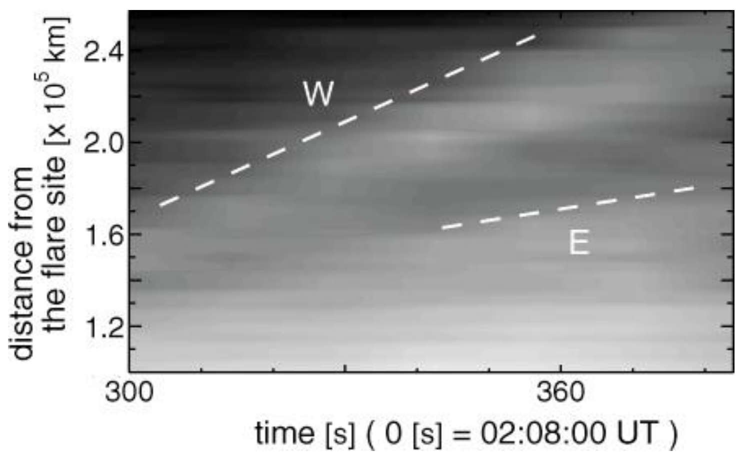
➔ What is the driver of waves?



Moreton wave
02:13:57

filament eruption
02:25:00

X-ray wave
X-ray ejecta
02:13:57



3 SOT target

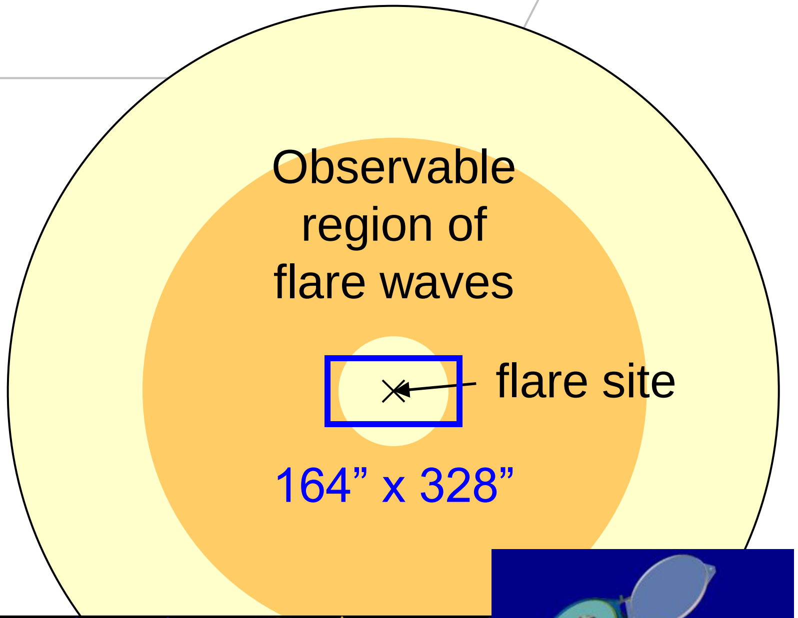
Solar Optical Telescope

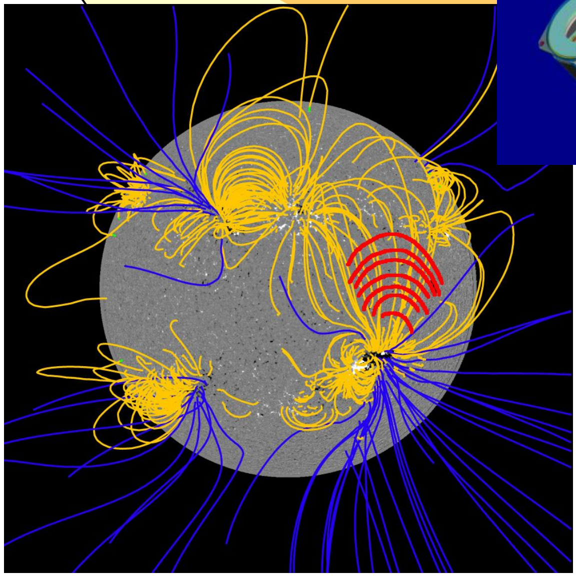
- filament eruptions are strongly related to the Moreton waves.

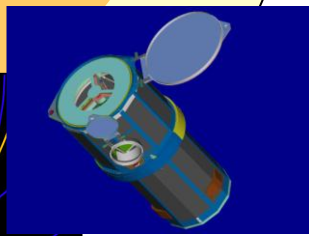
  ➔ We expect to detect the origin of Moreton waves (shock waves).

- We want to examine the shock generation mechanism.

  ➔ We expect to observe the magnetic field structure in the shock generated regions.







4 conclusion

- **<u>XRT</u>**
  - We can estimate the physical quantities of the shock waves during the propagation. Especially, the change of the quantities is important.
- **<u>SOT</u>**
  - We can know the magnetic field structure in the shock-generated flare region.
  - It may be possible to observe the shock generation.

➔ Using the above and ground-base observations, calculated global magnetic field, and numerical simulation, we can progress the study of the flare-associated waves.

5 Appendix

Solar-B

- The flare-associated waves would occur associated with 10% of X or M-class flares.
- If the flare frequency is the same as 11 years before, until 2009 there would be only a few waves per year. (This is underestimate.)

Year	2006	2007	2008	2009
X-ray wave	1	1	2	11

- Good observational plan is very important.

END

Thank you very much
for your attention.

quantities of X-ray wave

```
==================================================================
B_corona = B_photo * 0.5
==================================================================

 fr0=      1.9251738     fr =      1.9251785  (   2.4119677e-06)

 v1x=      652.93857     v2x=      501.06709
 Ix1=      15.601000     Ix2=      51.000599  (      51.000722)
 T1 =      2.2499993     T2 =      2.7754042
 B1 =      3.9905701
 theta1=   60.000000

 EM1=      43.544198     EM2=      43.774151
 em1=      27.042221     em2=      27.272174
 n1 =      8.4946216     n2 =      8.6095980

 Va =      492.46032
 Cs =      227.76080
 be =     0.25668277

 X  =      1.3030961
 vsh=      652.93857
 Mf =      1.2033978
```

noise

- Photon noise = $N^{1/2}$
- System noise < $30e^-$
- Dark = $0.1e^-$ / sec / pix

Conversion of photon to DN

- Photon → e^- 3.64eV = e^- + hole (in Si)
  conversion factor :
  1photon = 300e^- (except Thick Be)
- e^- → DN
  57e^- = 1DN

- XRT のみでの shock wave の判定は困難 → Moreton wave (Ha), Type II burst (radio) など地上観測との連携が必要。EIS での速度場観測も shock 判定に使える。
- Moreton wave の発生には filament eruption が必ず伴う → shock wave の origin か？ → SOTの高分解観測に期待。

DATA

- Capacity
  - Total : 8Gbits
  - XRT : 15% = 1.2Gbits
  - Loss less compress → 50%
- Data size [bits] = pix * pix *12bits