第11回 高エネルギー天文衛星

2021年6月15日 6:24

What are the three most essential performances in cosmic X-ray measurements?

Ideally, we would like to measure the X-ray photon energy, arrival direction, and arrival time.

However, we may not directly measure the X-ray photon energy ,arrival direction and arrival time.

What we detect is electric signals from X-ray detectors, and the detector resolution is limited.

1. Better spatial resolution → Good image
2. Better spectral resolution → Good spectra
3. Better timing resolution → Precise timing study

How can we design X-ray instruments to maximize the sensitivity (= signal to noise ratio)?

The larger the effective area, the more X-ray photons are collected. → Signals increased

Better to reduce the background noise (mostly electric particles [protons, electrons] in orbit).
The particle background is proportional to the dimension of detector.

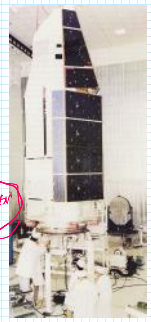
Focus X-rays using X-ray mirror into a small detector pixel (CCD, microchanel plate etc)

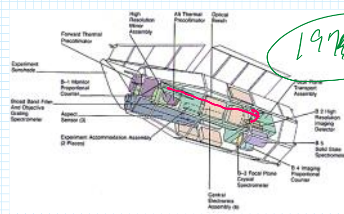
X-ray astronomy started in 1962, but the first X-ray imaging satellite using mirrors, Einsten, was launched in 1978.
Why it was so difficult to make X-ray mirrors? Give two reasons

https://chandra.harvard.edu/resources/animations/mirror_comparison_sm_2017.mov

Explanation of the principle of X-ray mirror

https://heasarc.gsfc.nasa.gov/Images/heao2/heao2_prepflight.gif





It was the first X-ray mission to use focusing optics with imaging detectors with an angular resolution of a few arcseconds, a field -of-view of tens of arcminutes. The sensitivity was several 100 times greater than any previous X-ray astronomy mission

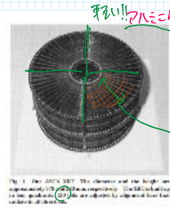
<https://heasarc.gsfc.nasa.gov/docs/einstein/heao2_about.html#instrument >

Einsten and ROSAT can image up to < 2 keV. X-ray imaging above > 2 keV was made possible with ASCA X-ray Telescope for the first time. ASCA is much smaller, lighter and cheaper than Einstein or ROSAT. Why this was made possible? What was the trade-off?

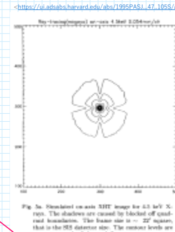
https://darts.isas.jaxa.jp/astro/asca/

http://cdsads.u-strasbg.fr/pdf/1995PASJ...47..105S

https://doi.org/10.1364/AO.34.004848

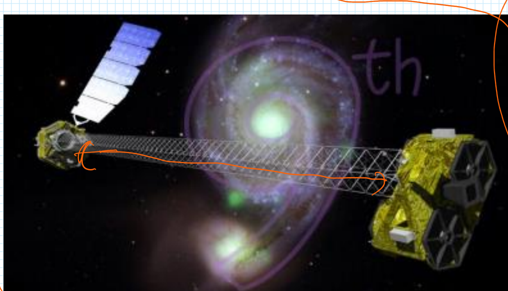


<https://ui.adsabs.harvard.edu/abs/1995PASJ...47..105S/abstract>

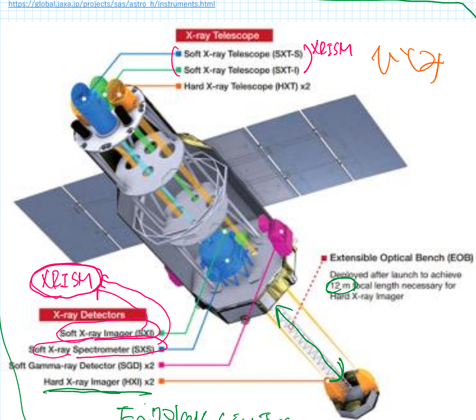


NuSTAR and Hitomi/HXI are the first satellites which can focus hard X-rays up to ~70 keV. How this was possible?

https://www.nustar.caltech.edu/news/126



https://global.jaxa.jp/projects/sas/astro_h/instruments.html



https://global.jaxa.jp/projects/sat/astro_h/topics.html

In 2023, what would be the best satellites/instruments for the following observations?

- Best X-ray imaging and sensitivity with the highest angular resolution in 0.5 - 10 keV → Chandra!!

https://chandra.harvard.edu/photo/2019/tycho/

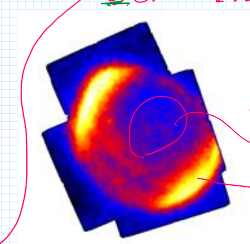
Tycho SNR by Chandra

Red soft X-rays
Green medium X-rays
Blue hard X-rays

SN1006 by Chandra https://chandra.harvard.edu/photo/2005/sn1006/

https://heasarc.gsfc.nasa.gov/docs/asca/gallery/sn1006.html

The first hard X-ray image of SN1006 by ASCA



→ E > 2keVで初めてイメージを取得した衛星
→ CCDでエネルギースペクトルを初めて取得した
1990年代

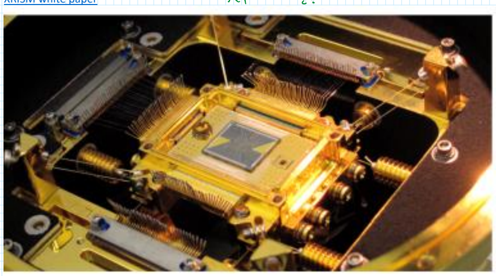
https://chandra.harvard.edu/graphics/resources/illustrations/craftOptBench4-72.jpg

https://chandra.harvard.edu/resources/ppt/telescope.html

← チャンドラ衛星のミラー
大きい!!
→ 空間分解能が高い → きれいなイメージが得られる

- High resolution spectroscopy in the iron K-band (6-7 keV) → XRISM!!

XRISM white paper



X-ray microcalorimeter

← X線ひとつひとつのエネルギーを直接測定する ⇒ X線点源でも、空間的に拡がった天体でも同じ

ΔE ~ 7eV ← X線のエネルギーによらない、X線の空間的ひろがりによらない

エネルギー分解能 (Resolving power)

$\frac{E}{\Delta E}$ がEに比例する

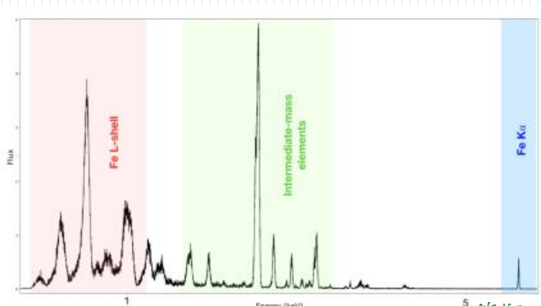


Figure 17: A sample spectrum that one might expect from a young Type Ia SNR, such as Tycho or Kepler's SNR. Lines from various elements or groups are highlighted. Lines are broadened due to the extremely high temperatures that result from gas being shocked by a 5,000 km s^{-1} shock wave. *XRISM* will resolve the widths of these lines in SNRs, leading to a direct measurement of the plasma temperature.

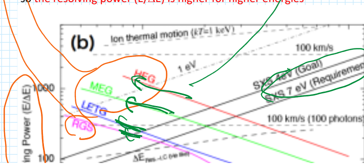
- High resolution spectroscopy at ~ 1keV for diffuse sources (e.g., supernova remnants, clusters of galaxies). ⇒ XRISM

- High resolution spectroscopy at ~ 1keV for point sources (e.g., stars, X-ray binaries). ⇒ grating (XMM, Chandra) の方が良い

XMM衛星のgrating
Chandra衛星のgrating (回折格子)
gratingはエネルギーが低いほどresolving powerが高い

https://pos.sissa.it/306/046/pdf (Ishida 2017)

For microcalorimeter, ΔE is constant (determined by accuracy of the temperature measurement), so the resolving power (E/ΔE) is higher for higher energies

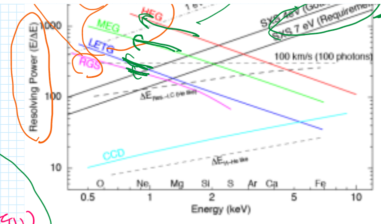


XRISMだとResolve (ほぼ同じスペック)
SXS — ひとみのマイクロカロリメーター

- High resolution spectroscopy at ~ 1keV for point sources (e.g., stars, X-ray binaries).

⇒ grating (XMM, Chandra) の方が良い

広がった天体には使えない



高いほうが Resolving Power が高い

For grating, spectral resolving power (E/ΔE) is higher for lower-energies
= wave-length resolving power (λ/Δλ) is higher for longer-wavelength

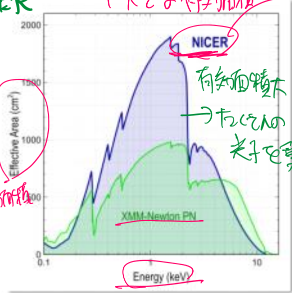
回折格子

- Very fast timing study (<< 1msec) for bright X-ray sources

速い分解能 + 大きな有効面積

NICER

- **Bandpass:** 0.2-12 keV
- **Effective area:**
  - >2000 cm^2 @ 1.5 keV,
  - 600 cm^2 @ 6 keV
  - *2x XMM-Newton for soft X-ray timing*
- **Energy resolution:**
  - 85 eV @ 1keV,
  - 137 eV @ 6 keV
  - *Similar to XMM and Chandra*
- **Time-tagging resolution:**
  - <300 nsec (absolute)
  - *25x better than RXTE*
  - *100-1000x better than XMM*
- **Spatial resolution:** 5 arcmin diam. non-imaging FOV



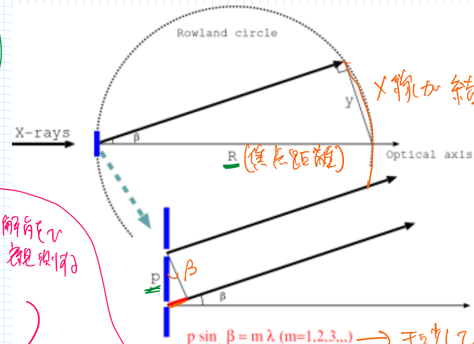
有効面積大 → たくさんの光子を集められる

位置分解能が非常に悪い (イメージが取れない)

ノイズは大きい

感度はそれほど高くない

https://heasarc.gsfc.nasa.gov/docs/nicer/nicer_about.html



X線が結像される

R (焦点距離)

光路差

干渉して強め合う

Δλ is determined by the position accuracy (Δy), not dependent on λ.

$p\sin\beta = m\lambda$

$R\sin\beta = y$

$p \cdot \frac{y}{R} = m\lambda$

衛星によって決まっている

$\frac{p}{R}(\Delta y) = m\Delta\lambda$

X線望遠鏡

$\frac{\lambda}{\Delta\lambda}$ Resolu...

1sec

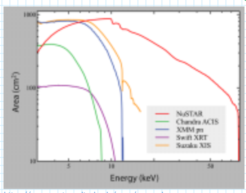
10^6 sec の分解能で観測する

大きな有効面積が必要 (1つ1つの時間ビンは 10^6 sec、1秒間に 10^6 個のビンがある)

有効面積が大

1秒間に 10^6 個のX線を検出した → 1ビンに1個くらいX線が入る

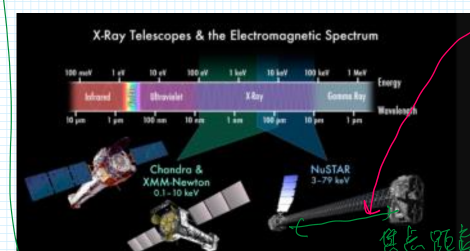
- Hard X-ray imaging above > 10 keV



https://www.nustar.caltech.edu/page/researchers

NuSTAR

長い焦点距離が必要

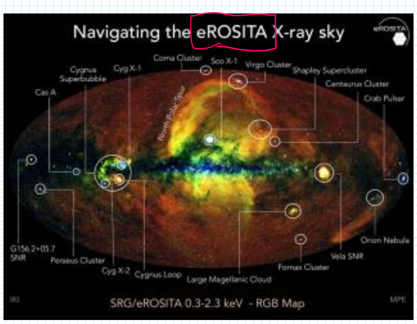


焦点距離が長い

https://www.nustar.caltech.edu/system/media_files/binaries/20/small/x-ray_comparison.jpg?1391213257

eROSITA

- Most sensitive all-sky X-ray image in 0.5 - 10 keV (no fast detection needed)



- Monitor all-sky in X-rays, discover bright X-ray transients and immediate follow-up X-ray observations

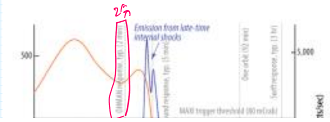
ISS (国際宇宙ステーション) 上で運搬

NICER will react to triggers from MAXI in an automatic way using a laptop computer on the ISS, in order to follow up on new transients within minutes compared to hours right now. This new rapid response to MAXI is called the On-orbit Hookup of MAXI and NICER or "OHMAN".

OHMAN プロジェクト

MAXI が自動的に新天体を検出

↓ (自動的に



(λ)
← 入射波長によらない

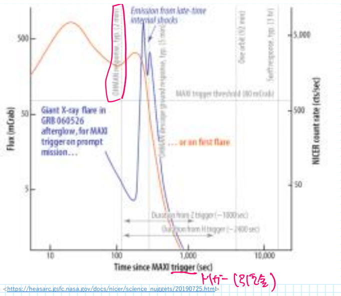
鏡の位置分解能

λが大きいほど高くなる

ing Power

Eが低いほど Resolving Powerは高い

$h\nu = \lambda \cdot E$

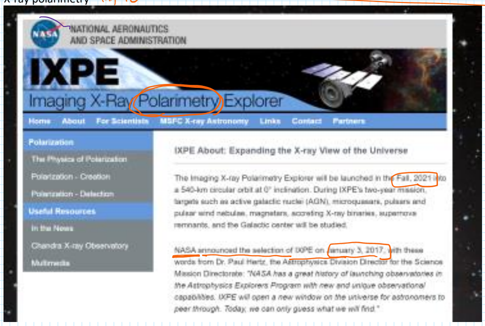


<https://heasarc.gsfc.nasa.gov/docs/nicer/science_nuggets/20190725.html>

トリガー（引き金）

MAXIが新天体を検出
↓ （自動的に）
NICERに伝える
↓
NICERが自動的に新天体の観測を開始する

- X-ray polarimetry 偏光

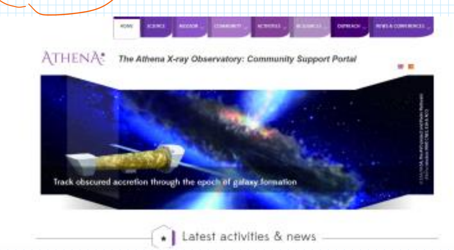

IXPE About: Expanding the X-ray View of the Universe

The Imaging X-ray Polarimetry Explorer will be launched in the Fall, 2021 into a 540-km circular orbit at 0° inclination. During IXPE's two-year mission, targets such as active galactic nuclei (AGN), microquasars, pulsars and pulsar wind nebulae, magnetars, accreting X-ray binaries, supernova remnants, and the Galactic center will be studied.

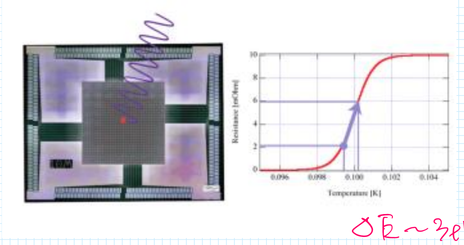
NASA announced the selection of IXPE on January 3, 2017, with these words from Dr. Paul Hertz, the Astrophysics Division Director for the Science Mission Directorate: "NASA has a great history of launching observatories in the Astrophysics Explorers Program with new and unique observational capabilities. IXPE will open a new window on the universe for astronomers to peer through. Today, we can only guess what we will find."

In early 2030's, which X-ray astronomy satellite will be operating? What will be the main instrument? How will be the performance?

https://www.the-athena-x-ray-observatory.eu/

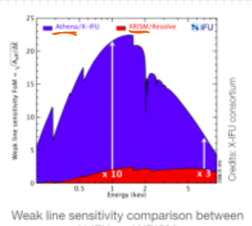


https://www.the-athena-x-ray-observatory.eu/11-news/555-athenanuggets-balancing-on-the-edge-detecting-x-rays-with-transition-edge-sensors.html



ΔE ~ 3eV

Much large effective area



Weak line sensitivity comparison between X-IFU and XRISM

ピクセル化

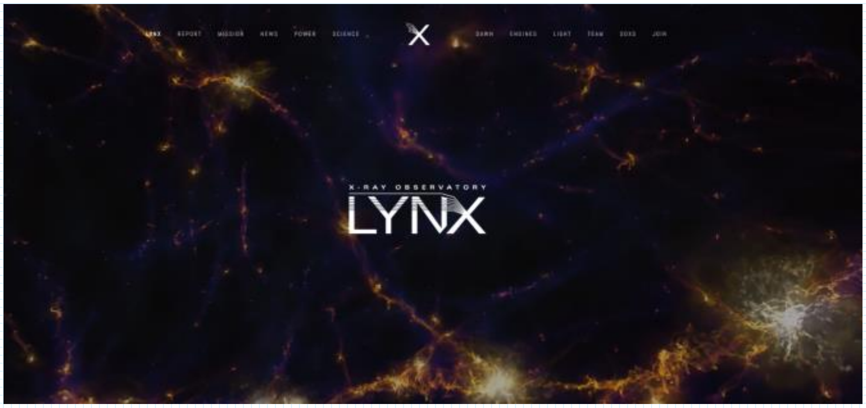
Pixelization of microcalorimeter X-IFU, unveiling the secrets of the hot and energetic Universe

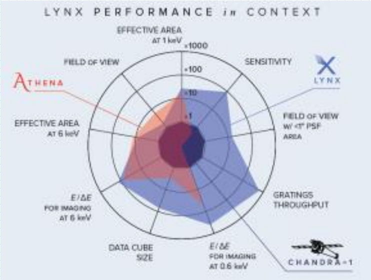
Transition Edge Sensor (TES) -- Utilize the "edge" of the super-conductivity and normal conductivity
Extremely senstive to the temperature change → better energy resolution

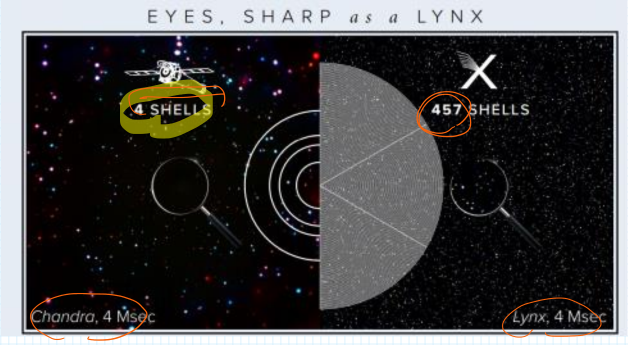
X線
↓ 温度が上がる
超伝導と常伝導の境 → 温度にsensitive → X線のエネルギーが正確にわかる
Transition Edge

In early 2040's, which X-ray astronomy satellite is expected to be launched? What would be the performance?

https://www.lynxobservatory.com/







2050年代の高エネルギー天文衛星プロジェクトを考えてみてください！