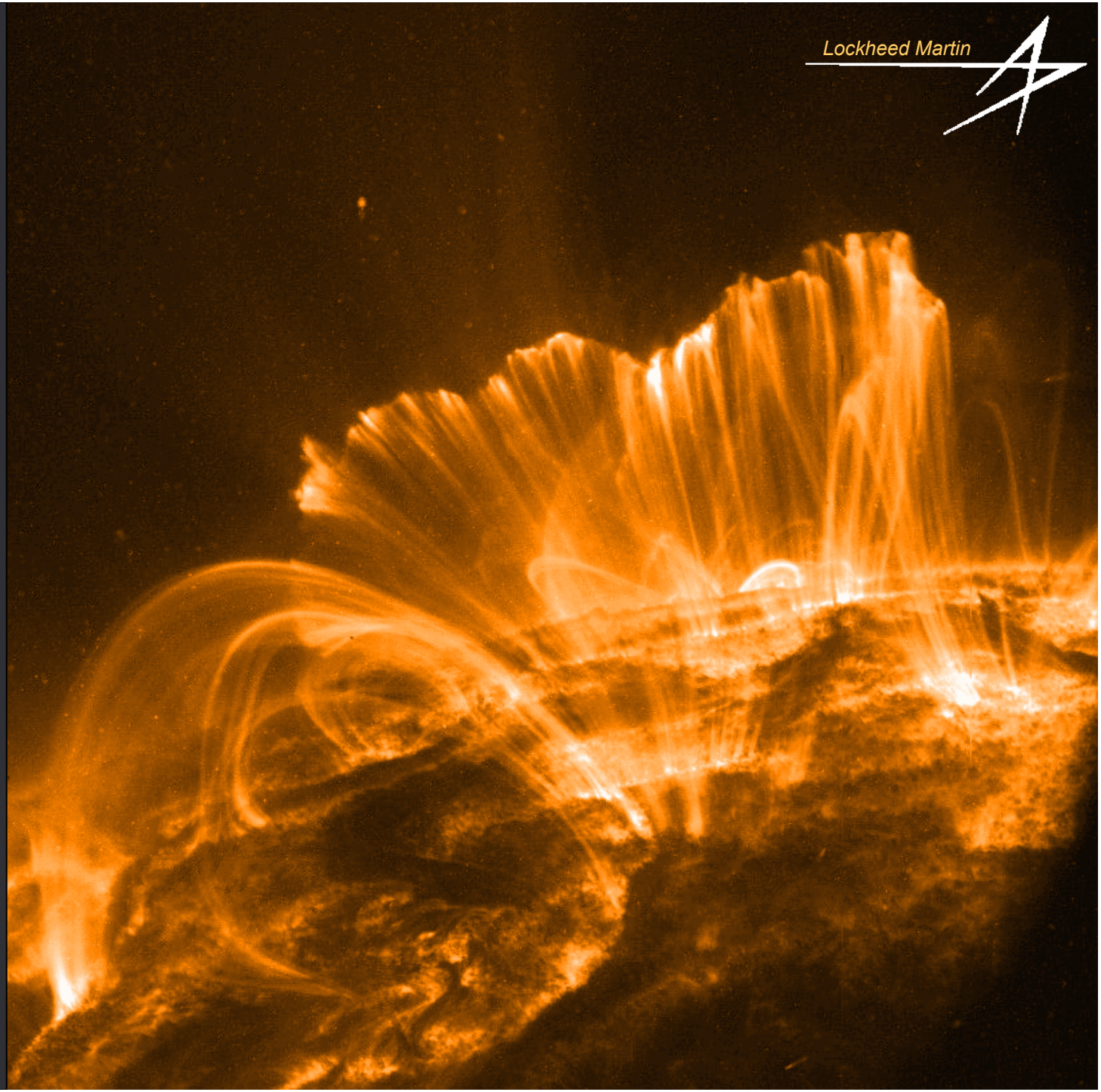
From Nano to Galacto…

Dennis Martínez-Galarce

Lockheed Martin Solar & Astrophysics Laboratory

Palo Alto, California
USA

www.lmsal.com



Overview

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- A Brief Walk Through Relevant Histories…
- Technologies employed for use in Solar & Astrophysics Observations…
- Views of our Galaxy… and beyond to the far distant past…
- Observations of our Sun…
- Future Technology in Solar and Astrophysics

"Grand Papá" of "X" Radiation

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- **Wilhelm Conrad Röntgen** (27 March 1845 – 10 February 1923) was a German physicist who, on 8 November 1895, produced and detected electromagnetic radiation, then called "X" radiation… and today called "X-rays". This achievement that earned him the first Nobel Prize in physics in 1901.
- Röntgen was investigating external effects of various types of vacuum tube equipment when he detected discharges from the tubes causing light shimmerings on a flourescent screen sitting on a bench, a meter away.
- Röntgen's meticulous attention led him to note the fascinating properties of the ability of X-rays to penetrate ordinary matter, passing through several that are opaque to visible or ultraviolet (UV) light.
- This then, was the humble beginning of X-ray physics, afterward pioneered by Max von Laue, William Henry Bragg and son, Lawrence, and Arthur Compton… and of course, now including many members in this audience!

'Sounding' Balloons and Cosmic Rays

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- **1783:** "sounding" balloon experimentation was slowly maturing… French physicist J. A. C. Charles rose in a balloon to approximately 3000 meters and measured a temperature 12 C lower than the ground.
- **1898:** Using un-manned balloons Researchers L. T. de Bort and R. Assman, independently discovered the "stratosphere" - that region of the Earth's atmosphere (~ 20 – 60 km) where the temperature remains constant. Interest also arose amongst a small group of physicist wanting to go to even higher altitudes to study phenomenon called "cosmic rays"….
- **1912:** Austrian scientist, Victor F. Hess, determined that radiations that struck the Earth were from beyond the atmosphere and non-solar in origin.
- **1931:** Italian physicist, Bruno B. Rossi, designed a cosmic ray "telescope", which used a high voltage (~ 2000 V), gas-filled tubes (invented by Hans Geiger & Walther Muller). This tube produces a "pulse" when a cosmic ray ionizes the gas inside.
- The advent of these discoveries has made *sounding balloons* a routine method for observing the Earth's inner/outer atmosphere.

The Ionoshpere & The Sun…

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- **1869 – 1940:** independent observations of solar eclipses demonstrated emission of visible light coming from the outer portions of the solar atmosphere, called the “chromosphere” (color sphere) and “corona” (crown).
  - Chromosphere is layer lying closest to the visible portion of the solar surface, while the corona is that which extends far outwardly to several solar radii.
- **1924:** Naval Research Laboratory (NRL) was established (at the suggestion of Thomas Edison for war preparedness). The initial mission of the laboratory was to study the propogation of communication radio waves and the conditions which prompted their disruption.
  - Edward O. Hulburt and the ionospheric research team at NRL noted that communications were disrupted during solar flare events
- **1937:** spectral measurements by V. Edlén suggested the corona is a gas of heavier elements (Fe, Ca and Ni), at low densities and very high temperatures, upto several million degrees.
  - This hypothesis was not yet experimentally demonstrable due to inability to travel to Earth’s exoatmosphere (beyond 40 km in height).

Rocketry… pre-WWII

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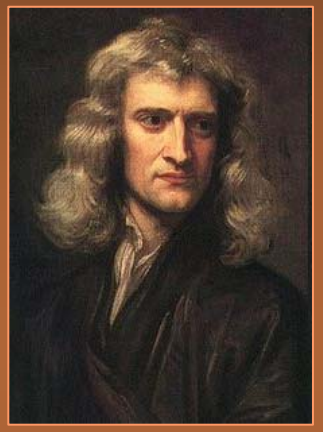
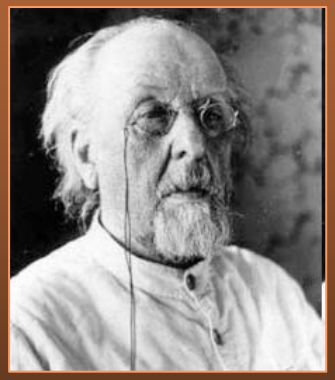
- **Ca. 1000 BC:** "rocketry" in its purest definition is traceable to the early Chinese, in association with the development of fireworks and gun powder.
- **17th Century:** Europeans began to develop this novel technology to advance war-making capability in the form of explosives and artillery projectiles. Further, with the advent knowledge of ballistics based on the theory of gravity and the Calculus (Isaac Newton & Gottfied Willhelm Leibniz), dazzling fireworks displays were created.
- **1806:** Italian Claude Ruggieri began to "rocket" small animals to high altitudes and recover them via parachute.
- **Late 19th & early 20th Centuries:** Russian Konstantin Eduardovich Tsiolkovskii (the "grandfather" of Soviet rocket engineering) developed the theoretical framework of the equations of motion that govern rockets, including some initial rocket designs.
  - Was the first to envision rockets as human transportation vehicles to outer space….



Sir Isaac Newton (4 January, 1643 – 31 March, 1727)



Konstantin Eduardovich Tsiolkovskii (5 September, 1857 – 19 September, 1935)

Rocket Science is borne!...

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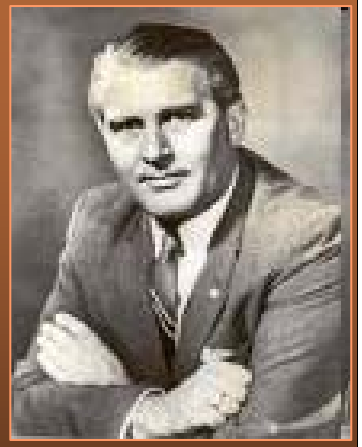
- **1926:** Robert H. Goddard, a U.S. Physicist, was the first to launch a liquid-fueled rocket.
- **1929:** An active rocket program was initiated in Germany as part of its effort to reestablish itself as a leading world power.
- **1944:** Toward the end of *WWII*, in a race to capture Germany's "rocket scientists" and take control of its remaining technology, U.S. soldiers beat the Russians in finding Werner Von Braun and Peenemünde, the fabrication center of the V-2 Rocket.
- **1945:** The Army announced the availability of V-2 rockets for use in high-altitude scientific experiments. E. O. Hulbert and collaborators at NRL recognized the opportunity for using rockets to "sound" altitudes beyond 40 km.
  - **1946:** Using a V-2 rocket, the NRL group obtained first UV spectrum of the Sun on film.
  - **1948:** T. Robert Burnright (NRL), used an Arobee rocket to detect the first solar X-rays on film.
  - **1949:** H. Friedman (NRL) flew Geiger counters on a V-2 rocket to confirm the X-rays were from the Sun.
- The latter discoveries were made only 53 years after Röntgen's initial discovery of X-rays!

Robert Hutchings Goddard
(5 Oct., 1882 – 10 Aug., 1945)



Werner Von Braun
(23 Mar., 1912 – 16 June, 1977)

Rocket Science in the Cold War Era…

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Late 1940s - '60s: W. Von Braun, upon arriving to the U.S., continued rocket R&D at the Redstone Armory in Huntsville, AL, eventually establishing the pathway to the Saturn rocket and the Apollo program. In 1970, W. Von Braun became NASA's Deputy Associate Administrator.

1957: "Sputnik I" is launched.. and the *Space Race* between the U.S. and the Soviet Union, going on since 1945… goes full throttle.

1958: In response to the "Space race" and threatening growth of the "military-industrial complex" the U.S. Congress established the creation of NASA. Also this year, American Science & Engineering (ASE) was established to conduct classified Space R&D; two notable members of ASE were Bruno Rossi and Riccardo Giacconi.

• Because of the "Cold War" political climate, the '60s period was beset with enormous political and scientific challenges in space research and technology development completely unseen during any other period of U.S. history and as a result, the U.S. space community enjoyed near-unlimited financial resources.

- as a consequence, UV & X-ray astronomy were but an unintended by-product of space & rocket science R&D efforts.

UV/X-ray Solar & Astrophysics begin…

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1956: J. E. Kupperian & H. Friedman (NRL) were first to detect extrasolar X-rays - a diffuse and near-isotropic background in all space now known as the *Cosmic X-ray Background*.

1960: First conference on X-ray astronomy took place at the Smithsonian Astrophysical Laboratory.

1962: R. Giacconi & collaborators launched Geiger counters on board an Aerobee rocket and detected the first extrasolar X-rays, whose source was dubbed "*Sco X-1*"

1963: Blake et al. (NRL) obtained the first high resolution X-ray spectra (λ < 25 Å (E_v > 496 eV)

1965: B. Rossi & R. Giacconi flew the first "nested" grazing-incidence X-ray telescope to record an image of the Sun (this design was an off-shoot of Hans Wolter's X-ray microscope).

As a result of the above findings… many groups formed at the NRL, The Aerospace Corp., Lockheed Corp., UC London / U. Leicaster, AFCRL, U. of Colorado and NASA that began intense space-based investigations in Solar & Astrophysics.

Pre-modern UV/X-ray Solar & Astrophysics

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1970s: Was the decade that introduced dedicated satellite observatories to study UV/X-ray solar and astrophysics:

1970: *UHURU* satellite was launched to study Cosmic X-rays using an anti-coincidence scheme of two proportional counters.

1972: Equipped with 3 proportional counters and a channeltron, the *Copernicus* satellite was launched to study FUV and soft X-rays in the Inter-Stellar Medium.

Early 1970s: The Orbiting Solar Observatories (*OSO*) were a series of small, low Earth orbiting satellites that carried a variety of instruments to study solar UV and X-ray phenomena.

1973 - 1979: *SKYLAB*, a manned space station, was used to carry several EUV and soft X-ray experiments to study the Sun; over 150,000 frames of film data were recorded.

Mid-late 1970s: *HEAO 1, 2 & 3 (*High Energy Astrophysical Observatory*)* were launched.

- HEAO-1 performed an all-sky survey in the 0.2 keV – 10 MeV range
- HEAO-2 (*aka* Einstein) was used to image and record spectra of X-ray sources found by HEAO-1 (0.15 keV – 4.5 keV)
- HEAO-3 had a gamma ray spectrometer and performed an all-sky survey, 50 keV – 10 MeV range.

Modern UV/X-ray Solar & Astrophysics

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1980 & 1990s: Marked a clear separation of science objectives that drove the development of sophisticated technologies requiring intricate and sophisticated instrument designs.

• Over time, certain technologies have been scaling smaller and smaller … down to *Nano* scales in order to optically probe in more depth our solar system and the Universe.

- X-ray solar & astrophysics which typically study very hot plasmas, $T > 10$ MK, drove the development of spectrographs using grazing incidence optics.

  - Primary Missions:
    - Einstein (1978 - 1982)
    - ROSAT (1990 - 1999)
    - SMM (1980 - '81, '84 -'89, solar)
    - EXOSAT (1983 – 1986)
    - ASCA (1993 – 2001)
    - YoHkoh (1991 - 2000, solar)

- EUV solar physics, which studies plasmas 10,000 K ≤ T < 15 MK drove the development of multilayer coated optics.

  - Primary Missions:
    - A series of sounding rocket experiments that used multilayer optics, primarily led by the Stanford-LLNL-MSFC and Harvard-IBM consortia (1986 – 2001).
    - SoHO (1995 - present)
    - TRACE (1998 - present)

What are the Critical Technologies Developed in EUV / X-ray Solar & Astrophysics ?

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• Not only did R&D in the 1980s & '90s improve on the technologies developed in the '60s & '70s, but it also introduced new technologies (CCDs and multilayer optics) that have been critical to improving our understanding EUV / X-ray Solar & Astrophysics.

- X-ray optics
  - Wolter 1 telescope (to study plasmas > 10 MK)

- EUV optics
  - Normal incidence multilayer optics (to study plasma more typically below 15 MK)

- To achieve high resolution imaging (< 1 arcsec) surface microroughness of the optics must be < 1 nm RMS!

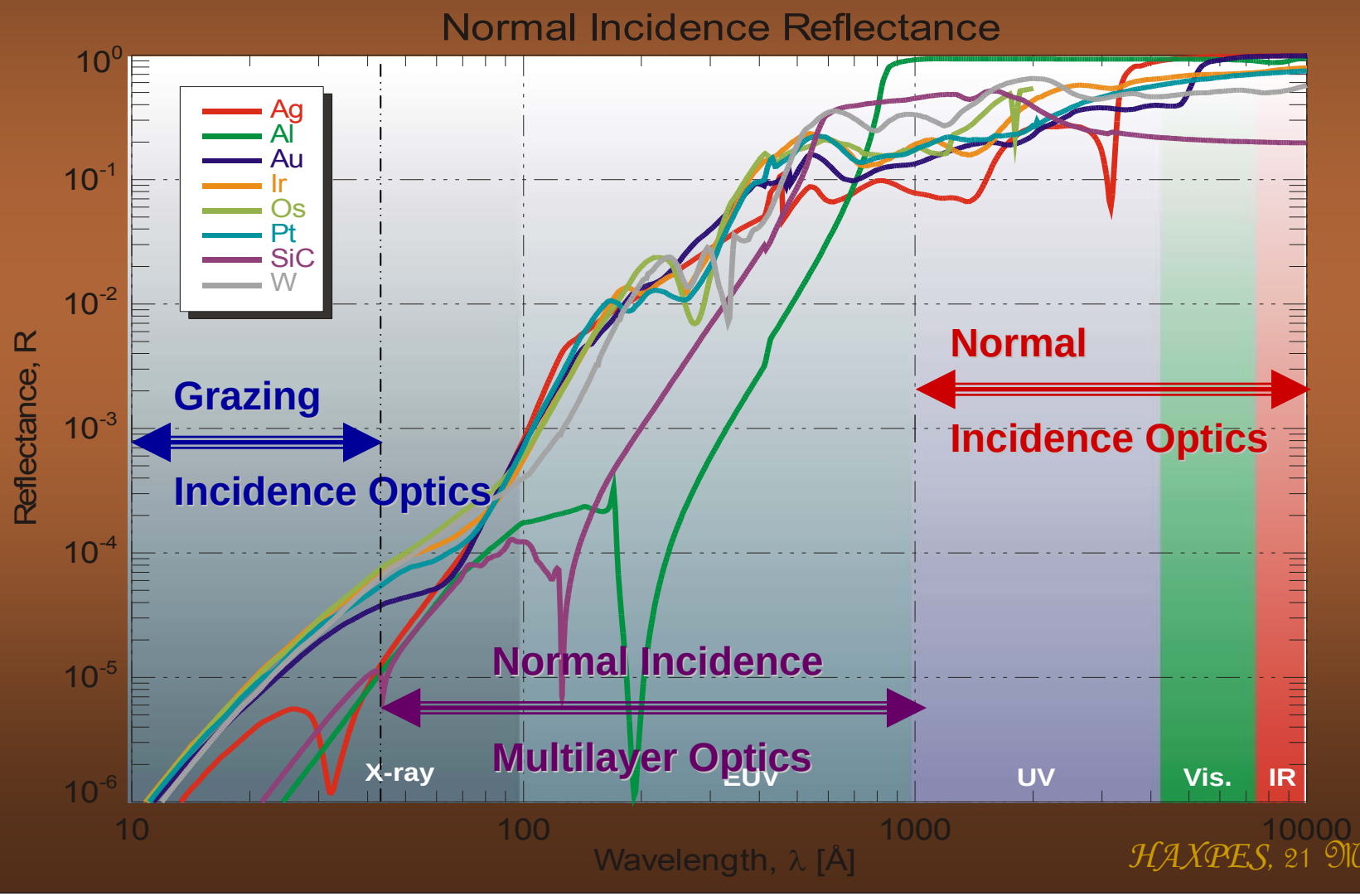
- EUV / X-ray Imaging Detector Technologies:
  - Film (grain sizes down to ~ 0.2 - 5 microns)
  - Charged Couple Devices (CCDs, pixels down to ~ few microns)
  - Low Temperature Detectors, namely, Transition-edge Sensors (TES), which cooled to ~ 100 mK and have pixel sizes down to ~ 200 microns)

Limitations of Normal Incidence Optics for the EUV and X-ray

Reflective X-ray Optics

Courtesy of D. L. Windt

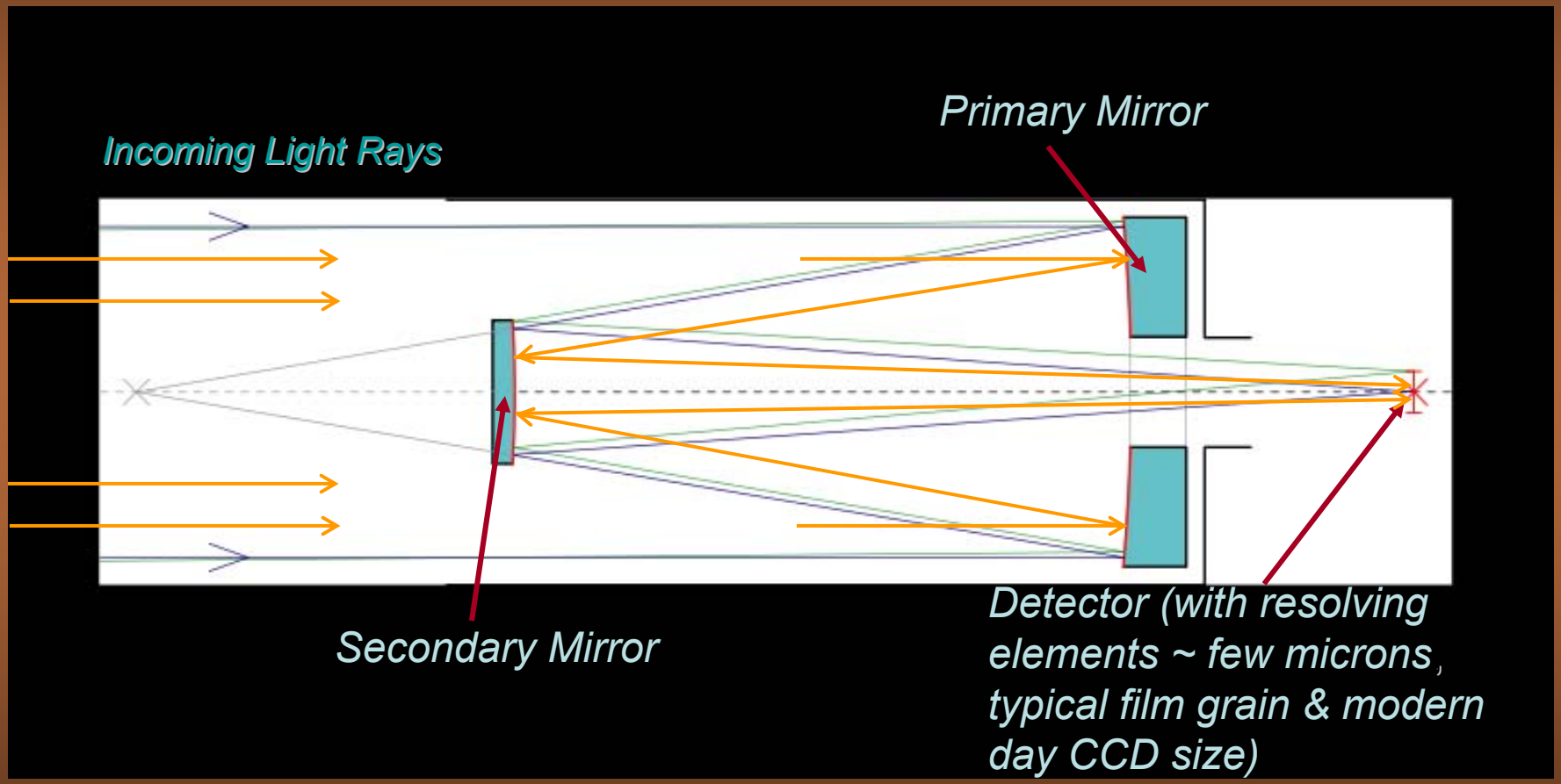
- Reflectance at normal incidence (i.e. ~90˚ to the reflective surface) for all materials begins to plummet in the extreme ultraviolet:



Normal Incidence (Cassegrain) Telescope

Reflective X-ray Optics

Courtesy of D. L. Windt



Grazing Incidence X-ray Optics (Wolter-I Telescope)

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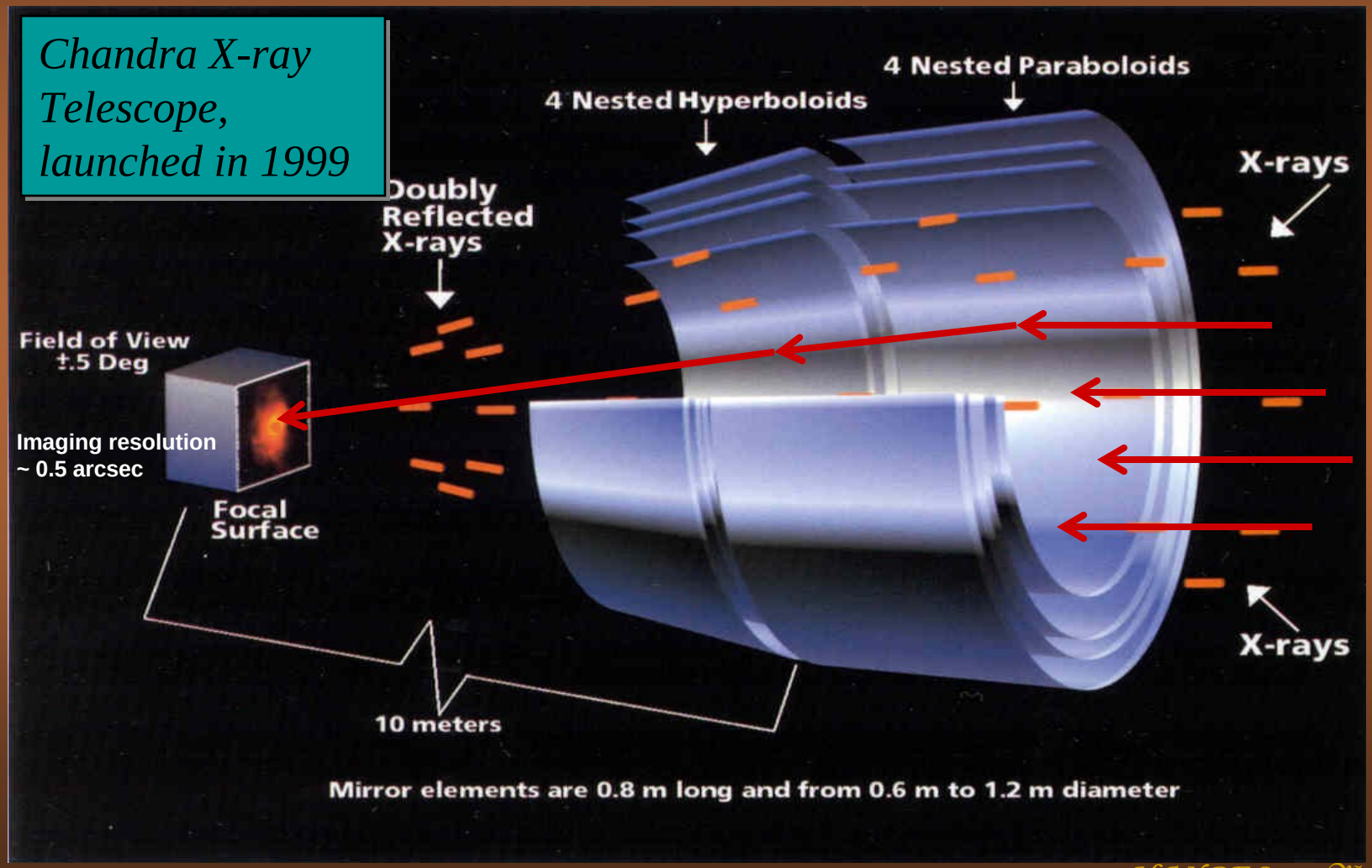
Grazing incidence optics of high resolution performance require polished surfaces with "micro-" roughness ~ few nm or less, down to spatial scales of ~ 50 nm



The Orion Nebula Cluster – A Region of Star Formation

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Chandra X-Ray Observatory

- This region shows over 1000 X-ray emitting young stars.
- These X-rays, like the Sun's are produced in the upper atmospheres of these stars.
- At 1800 light years, this cluster is the closest massive star-forming region to us.
- Image shown is approximately 10 light years across.

The Eagle Nebula

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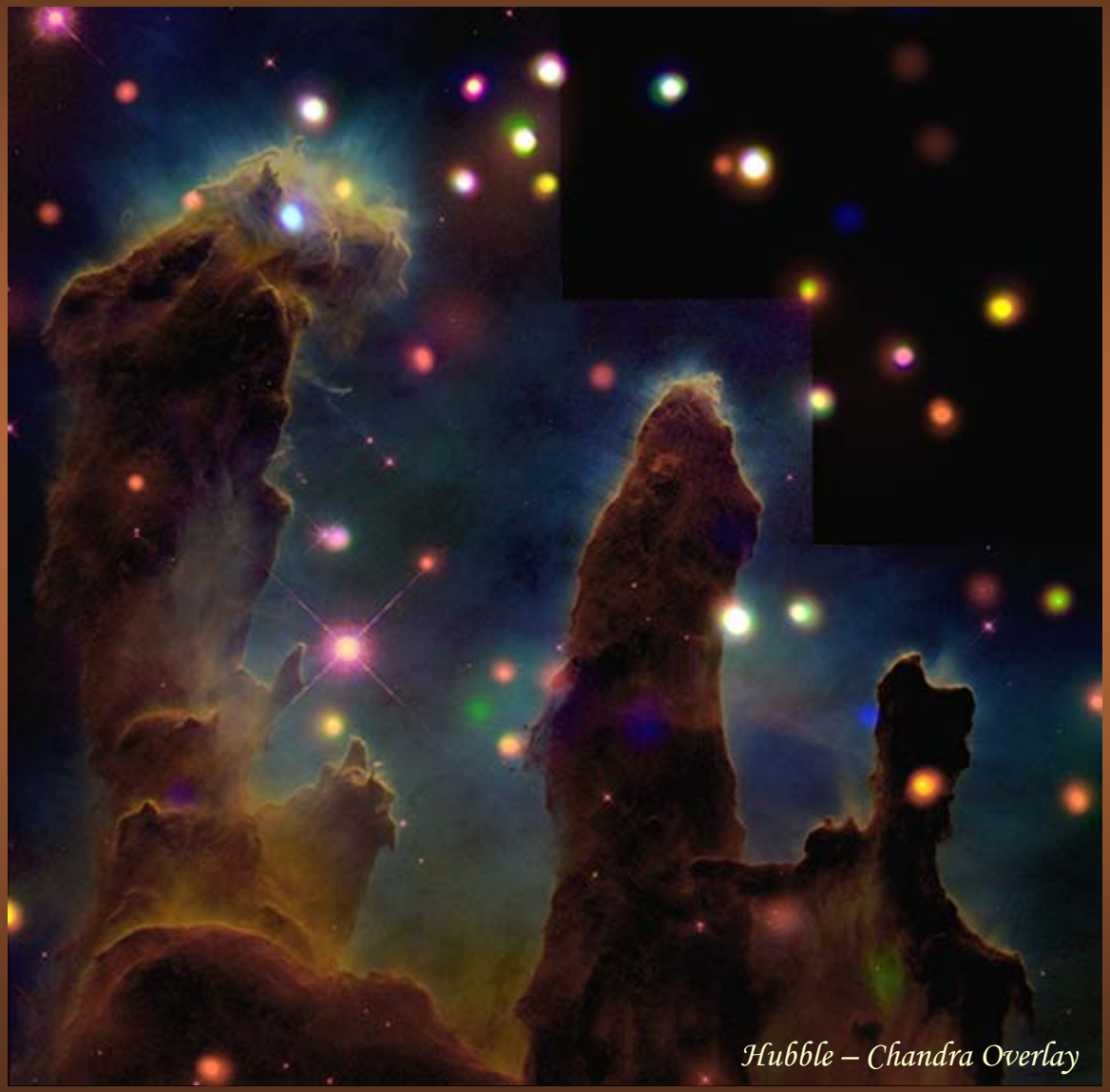
Chandra X-Ray Observatory



- In X-rays… the Eagle Nebula shows bright points that correspond to young, hot bright stars.

- Colors correspond to different X-ray energy bands ranging from 0.5 keV to 7.0 keV

- The "Pillars of Creation" show the dark columns of gas and dust where star formation is taking place.

- Few X-ray sources are found in the pillars themselves which suggests the Eagle Nebula may be past its star-forming period…

Crab Nebula

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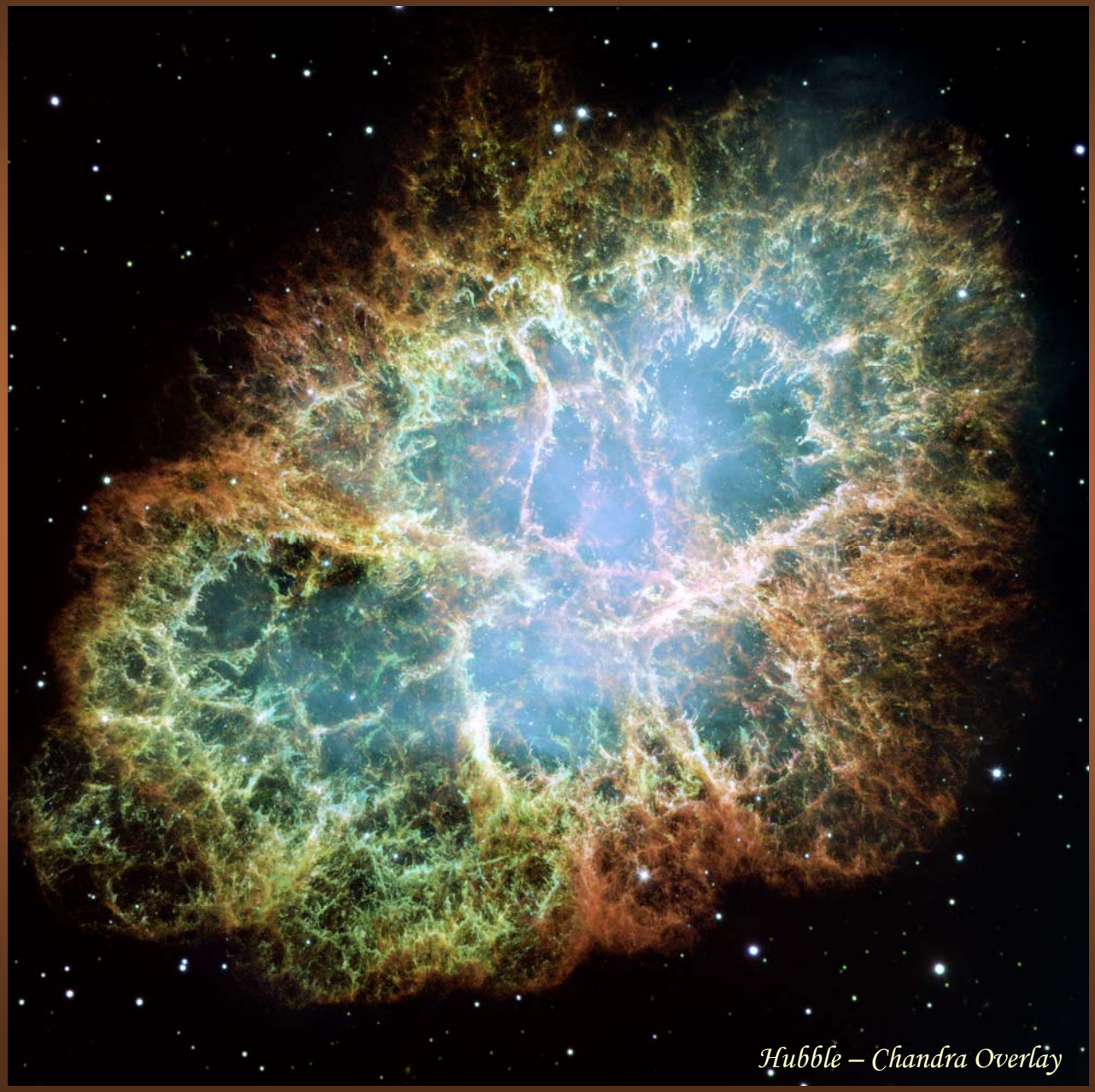
Chandra X-Ray Observatory



- The Crab Nebula has at its center a fast rotating neutron star (pulsar) that, coupled with its very strong magnetic field that generates an electro-magnetic field that creates jets of matter and anti-matter moving away from its poles.

- Inner X-ray ring is thought to be a shock wave marking boundary between surrounding nebula and the flow of matter and anti-matter from the pulsar. Electrons & positrons move outward from ring to brighten outer ring and produce extended X-ray glow.

M81 Galaxy

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Chandra X-Ray Observatory

- X-ray images allow astrophysicists to peer into the center of a galaxy and see its insides…; here we see a massive black hole and thousands of stars that emit X-rays produced in stellar atmospheres.

- When overlayed with optical observations from Hubble, we can clearly see the composite structure of the galaxy and the massive black hole at its center, feeding on nearby stars being “sucked” in by the huge central gravitational forces.

Centaurus A Galaxy

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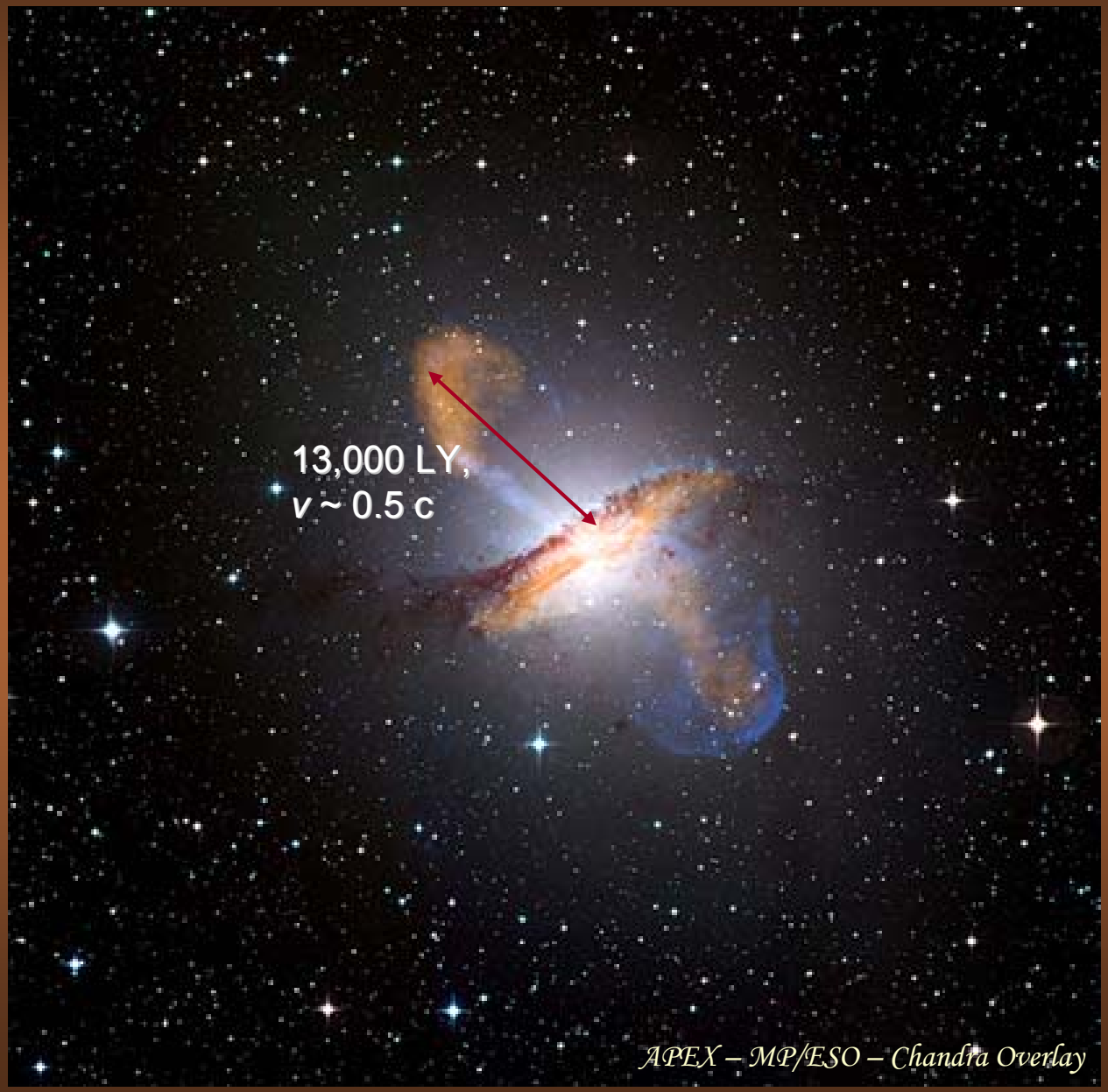
Chandra X-Ray Observatory



- A supermassive black hole exists at the galaxy's center which powers a prominent X-ray jet.
- Supermassive black hole powers jets and lobes, seen by sub-millimeter observations (orange, APEX telescope).
- Visible image from MP / EXO telescope shows dust lanes in galaxy's central disk.

Perseus A Galaxy in Perseus Cluster

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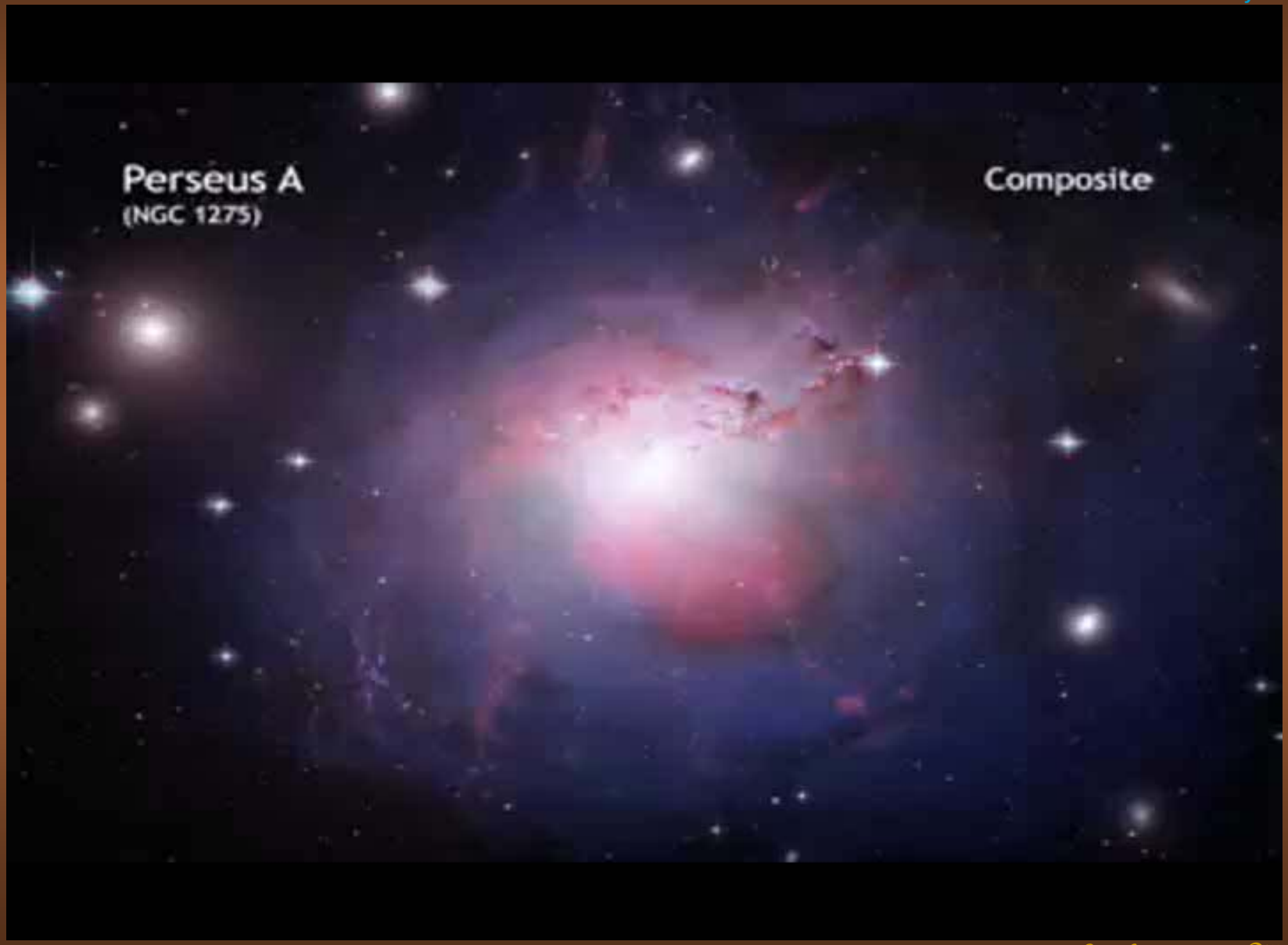
Chandra X-Ray Observatory



The "Bullet" Cluster

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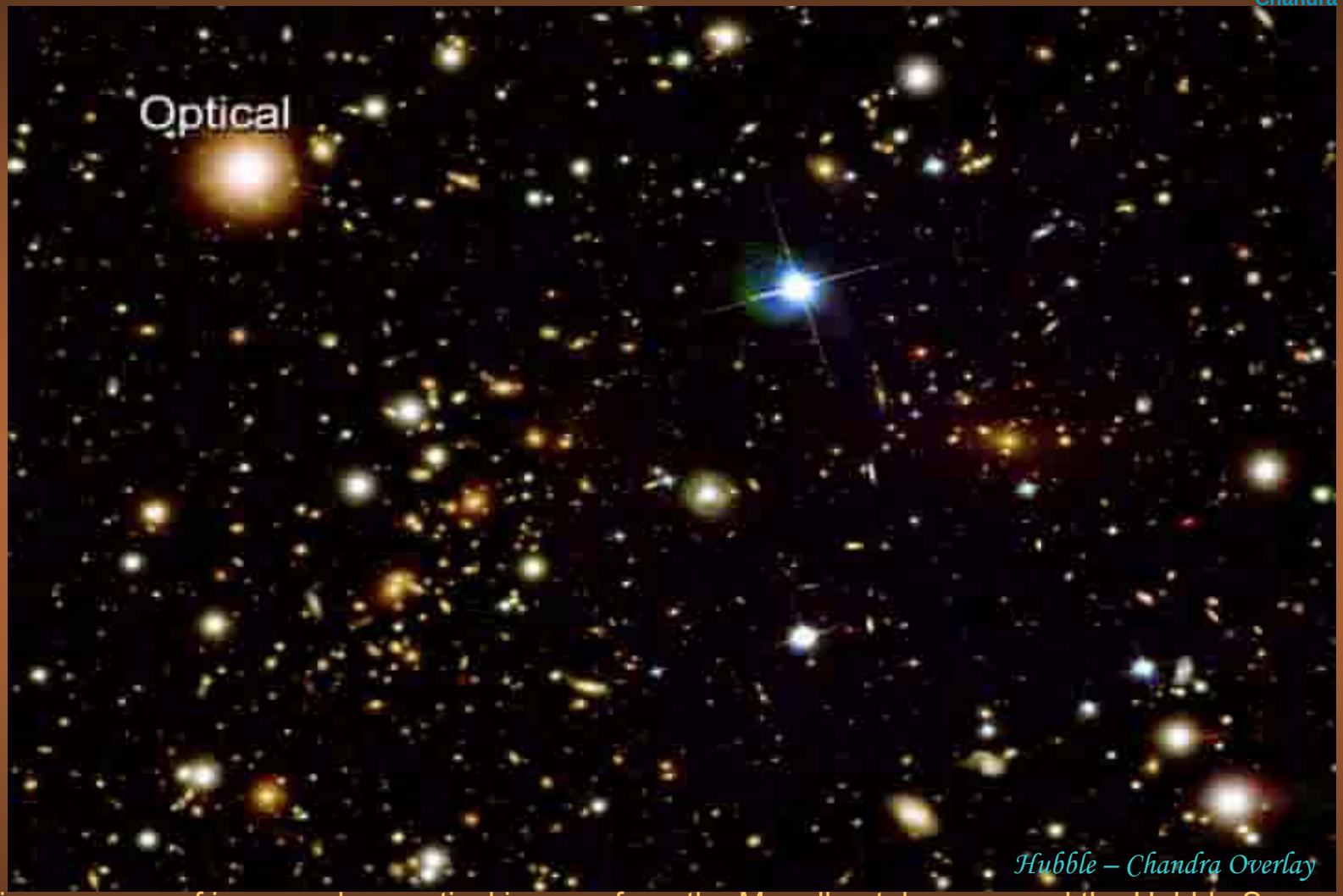
Chandra X-Ray Observatory



• This sequence of images show optical images from the Magellan telescope and the Hubble Space Telescope with galaxies in orange and white; hot gas, which contains the bulk of the normal matter in the cluster is shown by the Chandra X-ray image (pink). Gravitational lensing, the distortion of background images by mass in the cluster, reveals the mass of the cluster is dominated by dark matter (blue).

MACS J0717 – Massive Galaxy Cluster

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Chandra X-Ray Observatory

MACSJ0717 is composed of clusters of galaxies that have been in repeated collisions over a 13-million-light-year long stream of galaxies, gas and dark matter.

Courtesy of H. Ebeling, IFA, U. of Hawaii

Even Jupiter Emits X-rays!

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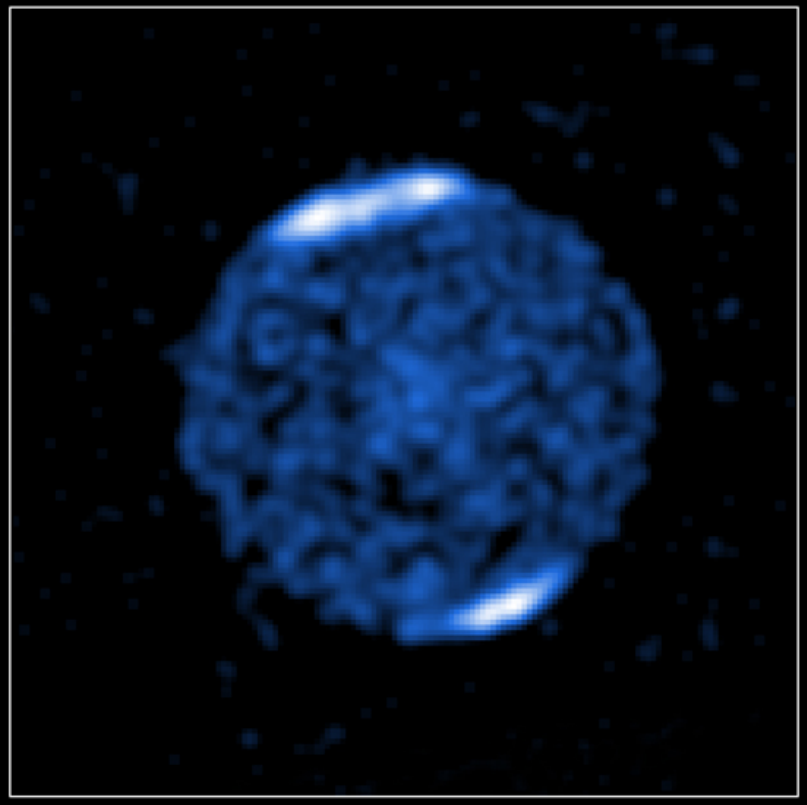
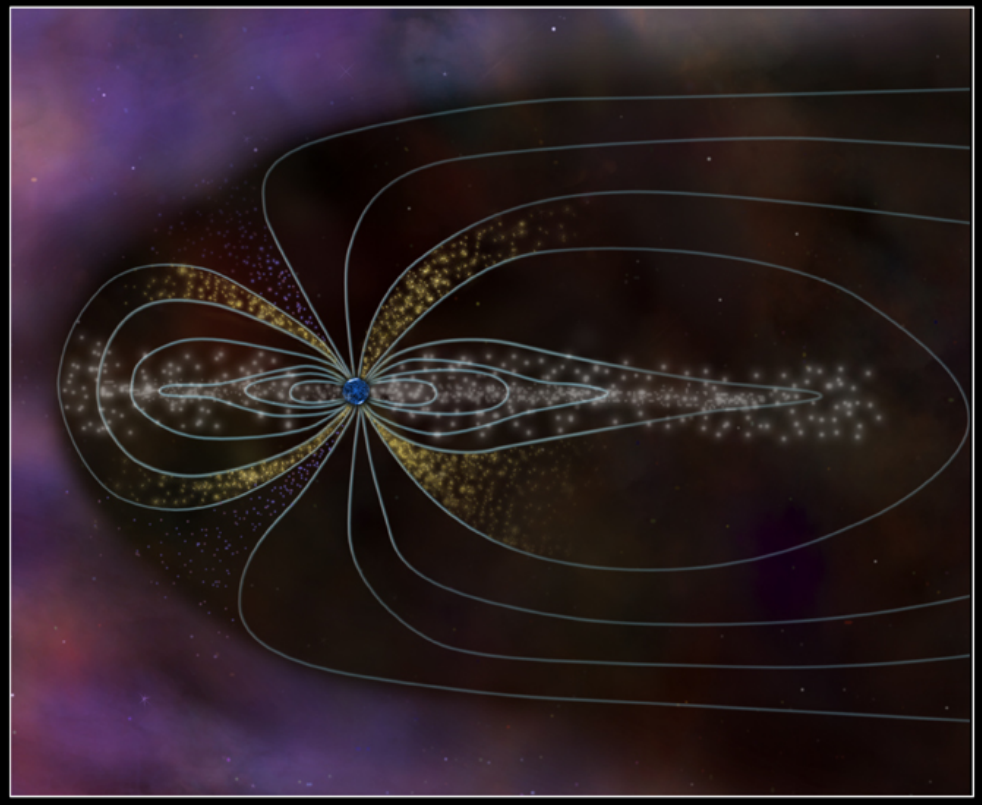
Chandra X-Ray Observatory



CHANDRA X-RAY OF JUPITER



ILLUSTRATION

Jupiter's X-rays are due to proton bombardment from the Solar Wind that is trapped in its magnetic field, bouncing back and forth between poles.

Our Sun

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- The Sun is the nearest star and is a “Main Sequence” star that is about 5 billion years old.

- It is composed mostly of Hydrogen (~ 91.2 %) and Helium (~ 8.7 %), with all other elements representing the remaining 0.1 %.

- Its surface is called the photosphere (what we see with our eyes…), while its atmosphere is composed of the chromosphere, transition region and corona.

- The temperature of the photosphere is ~ 5700 K; the chromosphere is between 10,000 – 30,000 K; the transition region is between 30,000 – 100,000 K and the corona is above it, rising up to 20,000,000 K (for flares and CMEs).

- These high temperatures are known to exist in its atmosphere because of the line emission detected at many wavelengths of the electromagnetic spectrum, but most notably at EUV and soft X-ray wavelengths.

- As mentioned previously, grazing-incidence Wolter telescopes and normal-incidence multilayer optical telescopes are the instruments typically used to image the Sun’s atmosphere at soft X-ray and EUV wavelengths, respectively.

Cassegrain (Normal Incidence) Telescope

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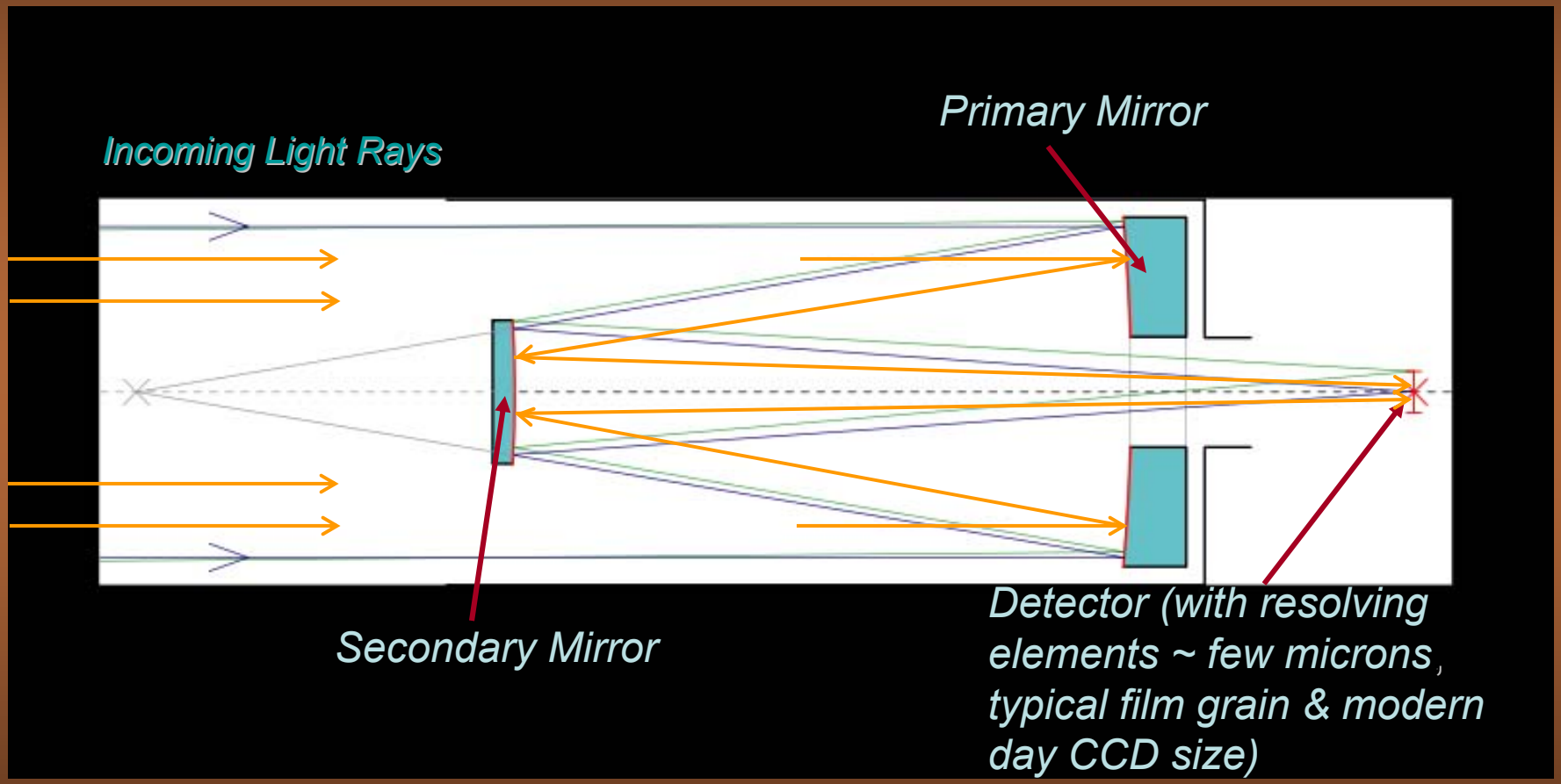

Multilayer Optics: What are Multilayers?

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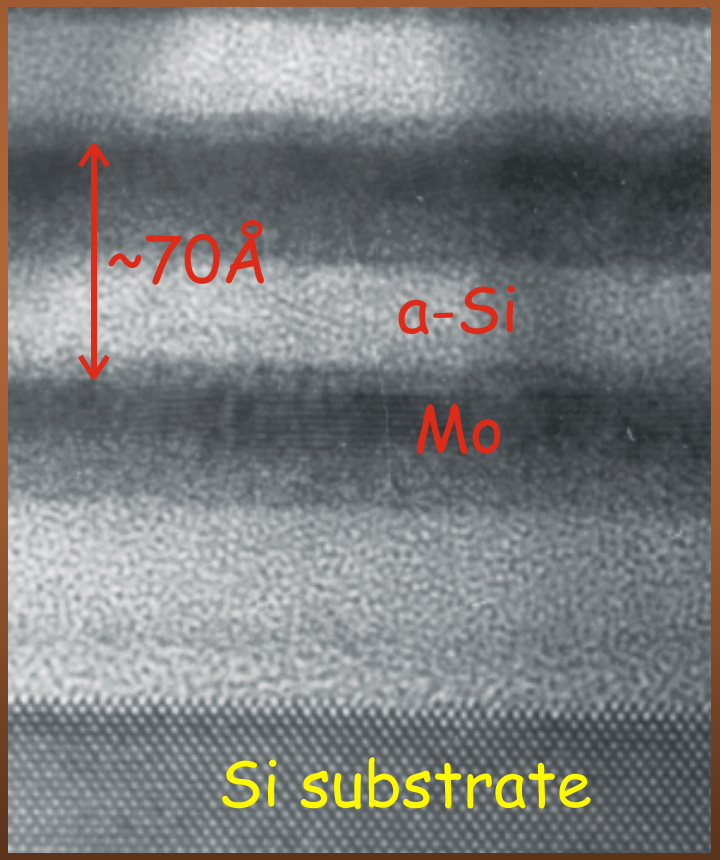
- **Multilayers are thin film depositions of 2 (or more) materials deposited as a repeating stack.**
- 1939: The first X-ray multilayer was fabricated by DuMond and Youtz. They deposited Au/Cu multilayers via thermal evaporation to perform the first X-ray measurement of diffusion in solids.
- 1972: E. Spiller first proposed use of multilayer coated optics to perform narrow bandpass, EUV / soft X-ray imaging of the Sun.
- EUV / soft X-ray multilayers are nanostructures that typically consist of:
  - Bilayer periods ~4 nm < d < 30 nm
  - N = 10 – 200 bilayers
  - Optically (and often microstructurally) are made of dissimilar materials
- 1987: First use of multilayers for EUV / Soft X-ray optics was performed by J. Underwood et al. (LBNL & Lockheed) on a sounding rocket to image a solar active region at 4.4 nm (282 eV).



(Figure, Courtesy of D. L. Windt, Reflective X-ray Optics)

Why are Multilayers of Interest to Solar Physics?

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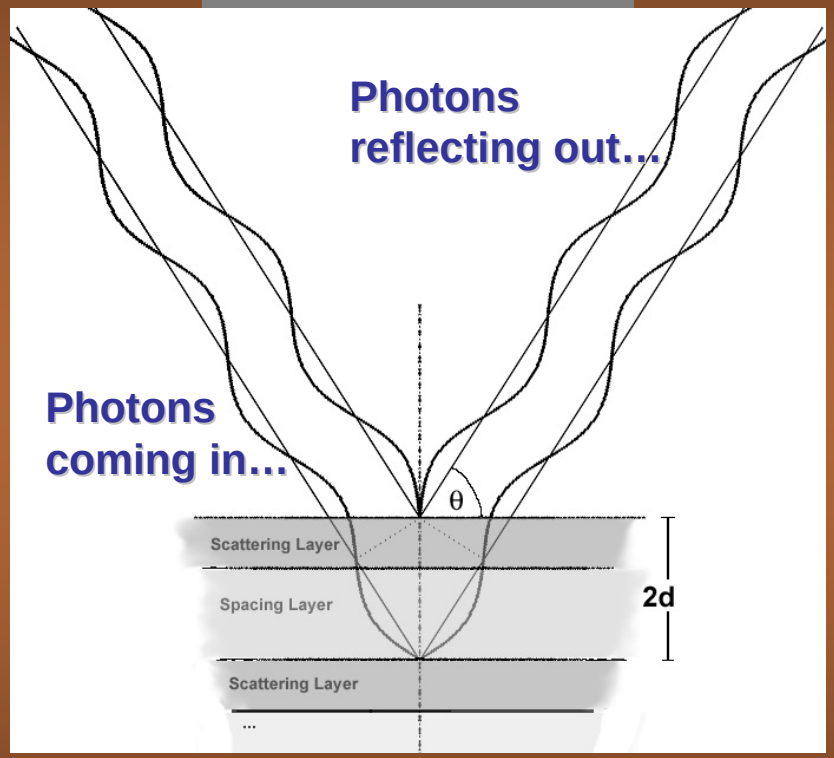
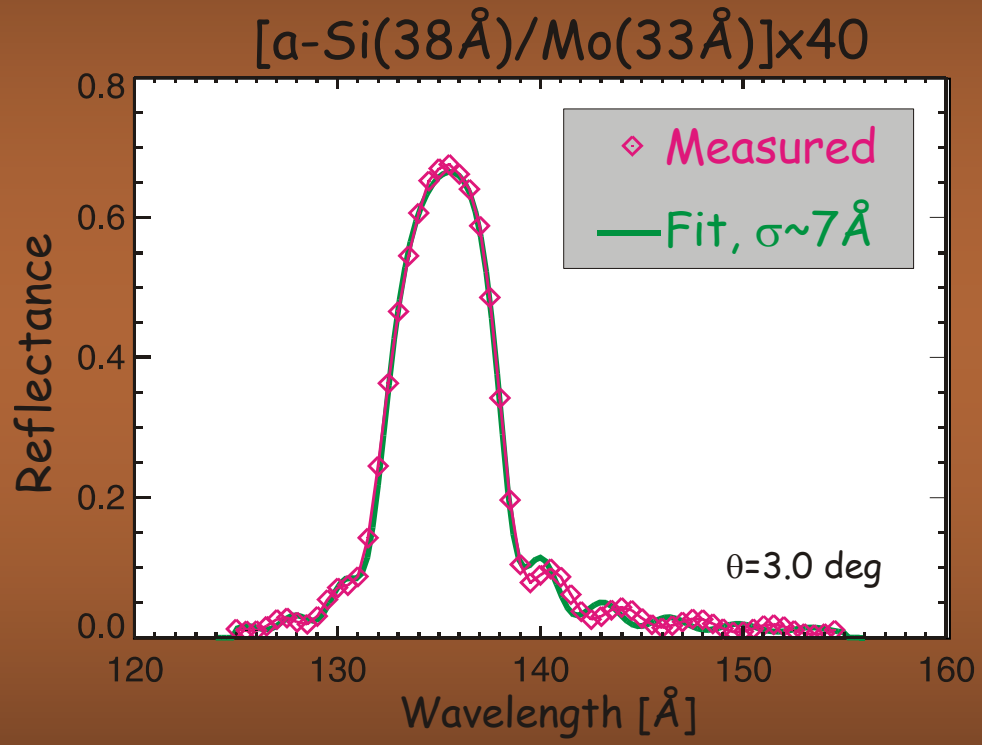
$$m\lambda = 2d\cos\theta$$



- *For a periodic multilayer, Bragg's Law governs reflection of EUV / soft X-ray photons, just as in a crystal.*

(Figure, courtesy of P. Boerner, LMSAL)

Multilayers enable operation at EUV wavelengths, at normal incidence.



(Figure, courtesy of D. L. Windt, Reflective X-ray Optics)

Multilayer Development & Performance Optimization

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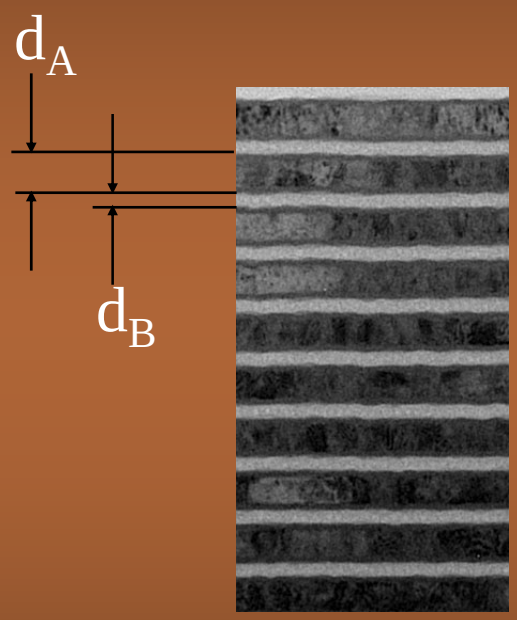
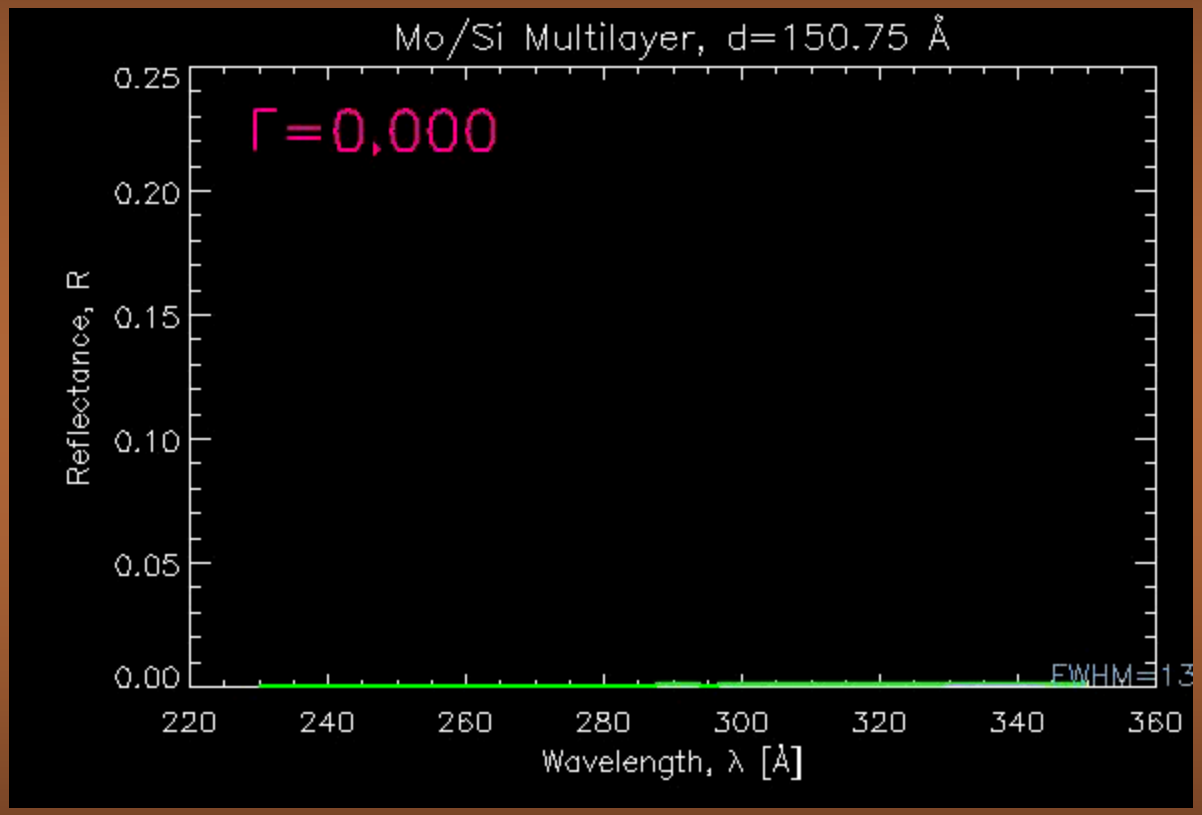
- The parameter Γ controls the spectral bandpass and peak reflectance.



$$\Gamma = d_A/(d_A+d_B) = d_A/d$$



- In the manufacturing of a multilayer coating, a "thru-Γ" series of test coatings is deposited on Si wafers and measured in order to determine the optimal bandpass performance at the peak wavelength selected.

Effect of Multilayer Interface Imperfections

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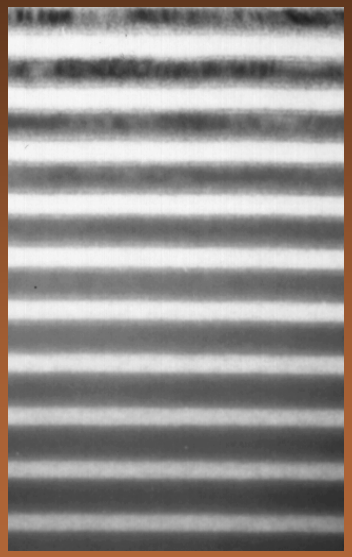
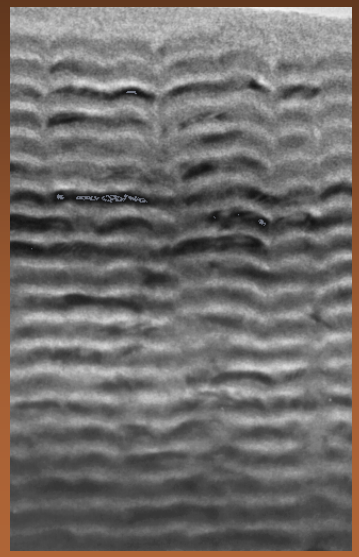
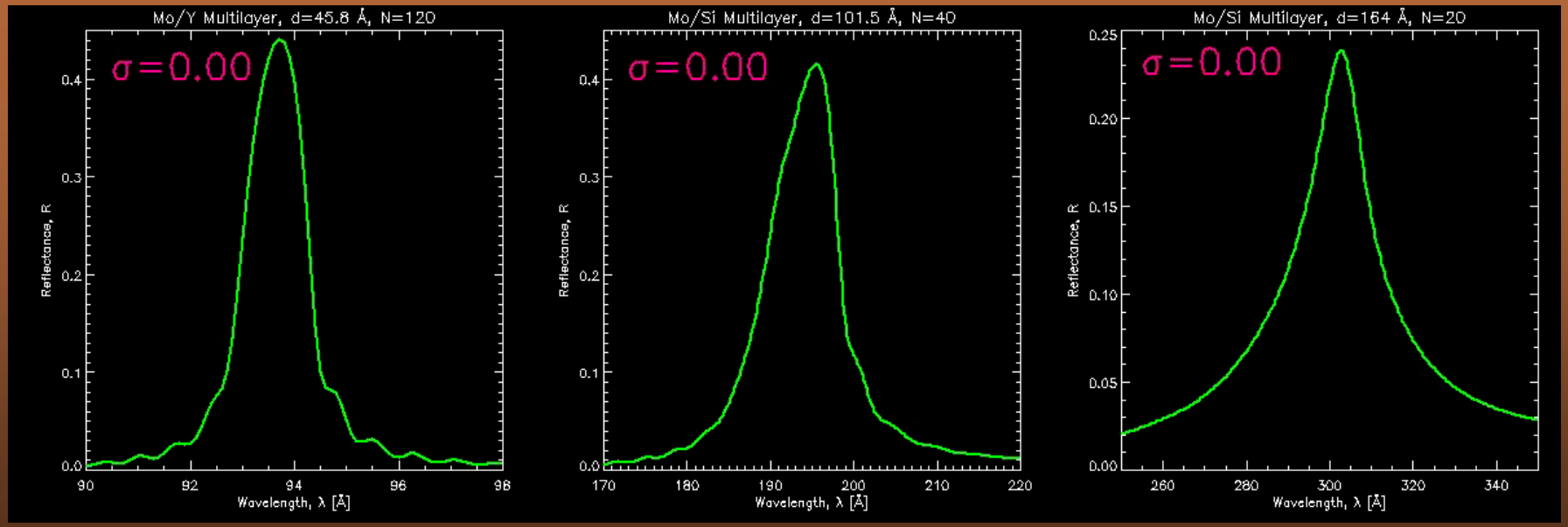
Two Mo/Si multilayers:

Ideally, one wants a multilayer stack to be uniform.





Non-uniformity during multilayer depositions will affect the EUV performance of the stack, i.e. the reflectivity.



Interface imperfections become increasingly important at shorter wavelengths.

Multilayers are Narrowband Tunable Filters

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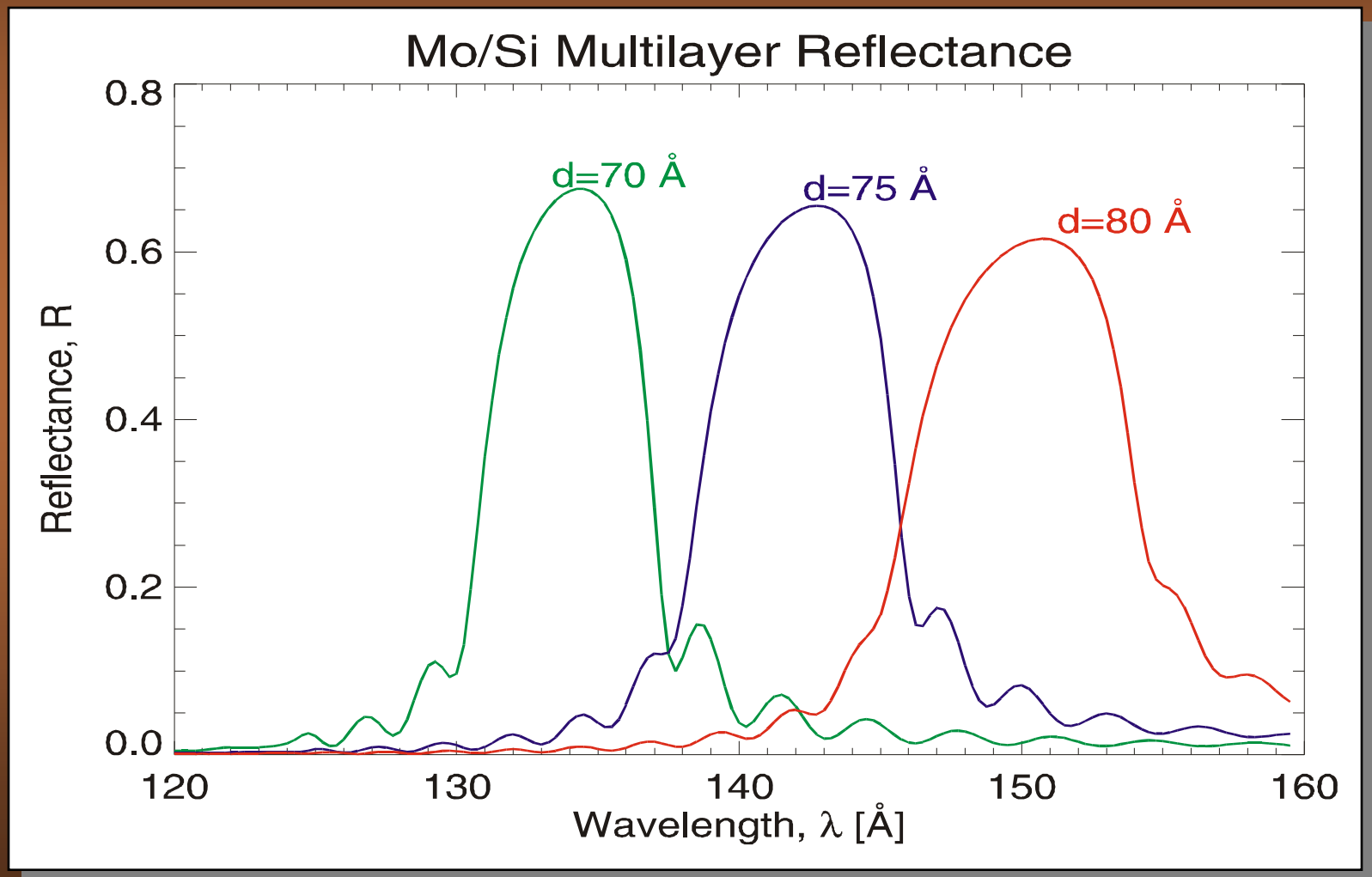
- Choice of materials, spacing (d) and Γ determine EUV performance.

$$m\lambda = 2d\cos\theta$$



Multilayer Coated Mirrors look Similar to Nominally Coated Mirrors

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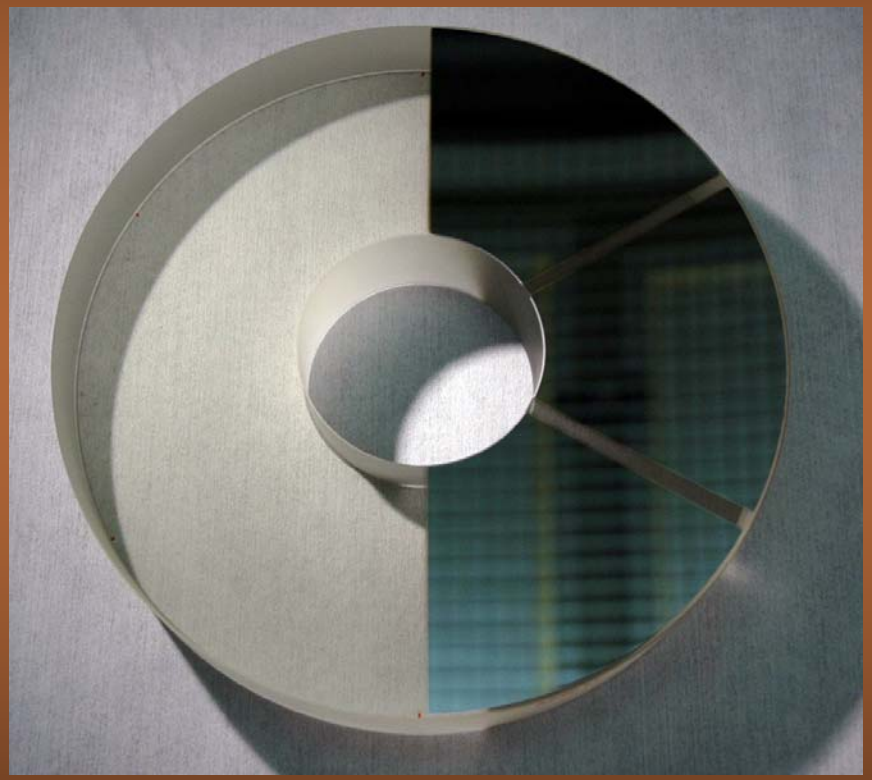
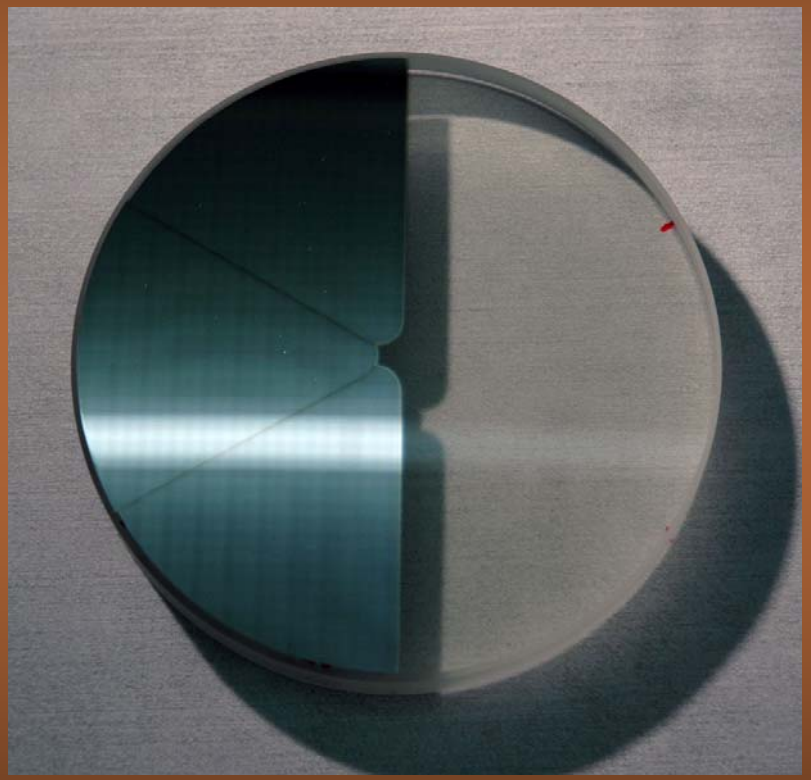
• Multilayer coatings are reflective at visible wavelengths, and have the same appearance as other typical metallic-coated mirrors.



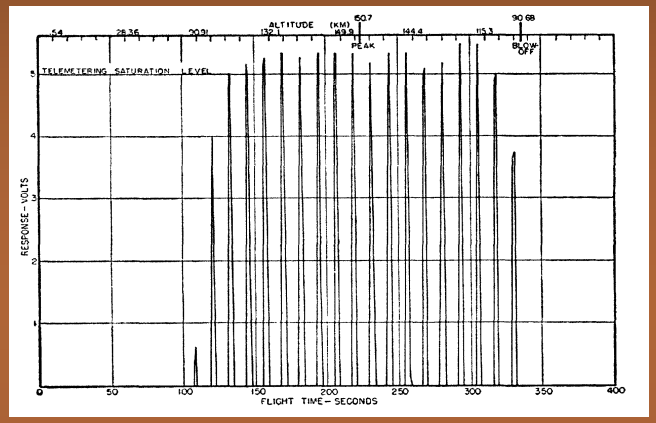


• Each coated sector shown here represents a different EUV channel that will pass solar EUV light selectively. Total multilayer thickness ~ few thousand Angstroms.

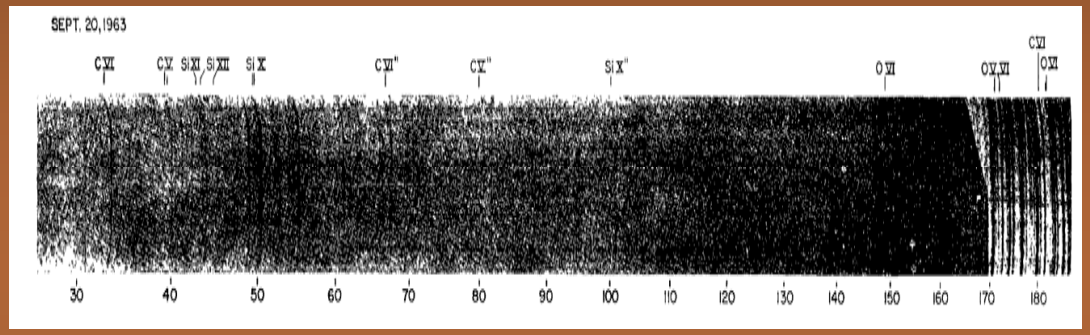
Early EUV / Soft X-ray Solar Spectroscopy

Lockheed Martin

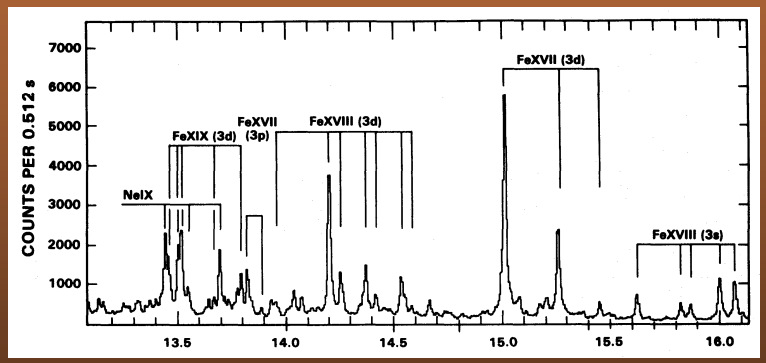
- Since 1949, a plethora of sounding rocket experiments have taken place to carry out EUV / soft X-ray solar spectroscopy. With each successive flight the observations were fine tuned and improved upon. However, since SMM (1981), no high resolution EUV / soft X-ray spectrometer has successfully flown to study the sun in a long observational campaign.



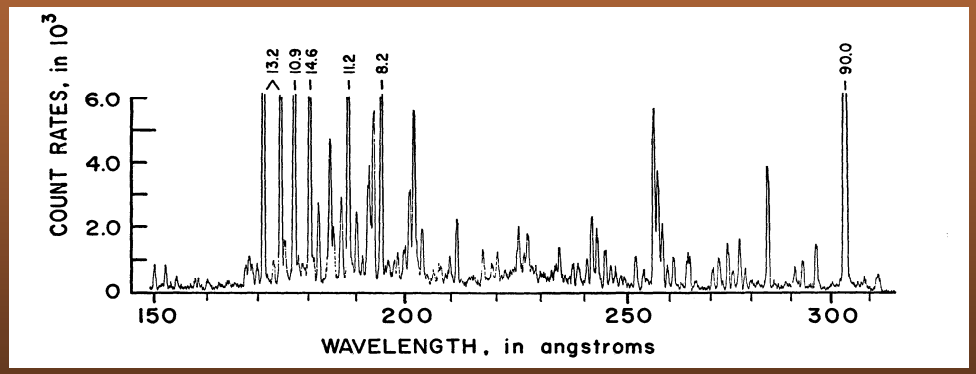
Friedman et al. 1951 (V-2 rocket)



Tousey. 1963 (sounding rocket)



Culhane, Acton & Gabriel et al. 1980 (SMM)

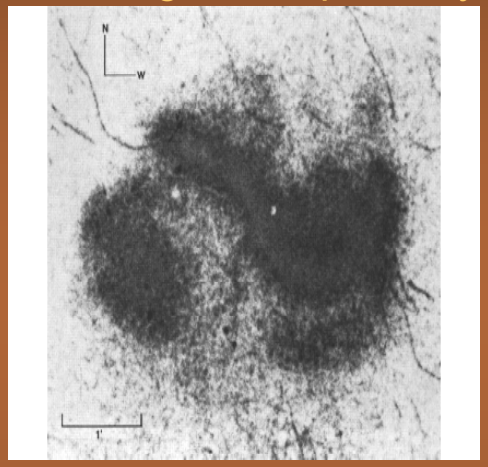


Hall et al. 1965 (OSO-III)

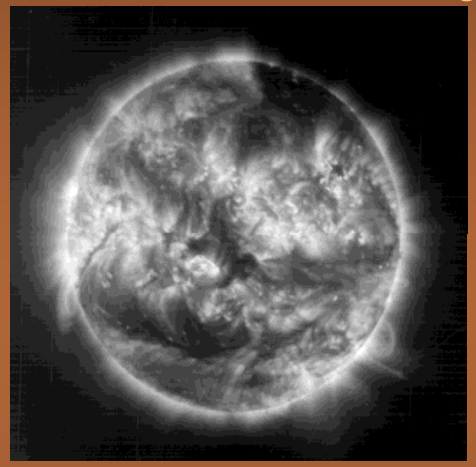
Modern EUV / Soft X-ray Solar Spectroscopy uses Multilayer Optics

Lockheed Martin

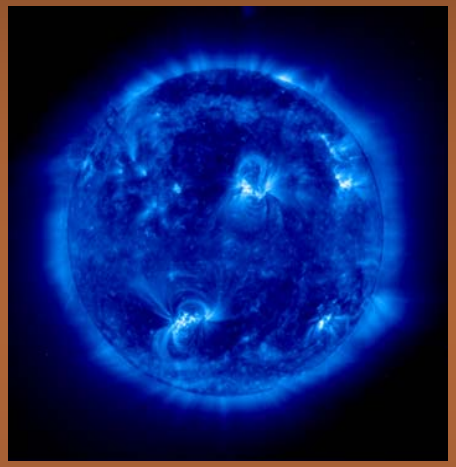
- Narrowband, normal-incidence, multilayer XUV solar imaging:
  - First "successful" imaged observation was recorded in 1987 on a sounding rocket (Walker et al. 1988) ==> demonstrating a novel powerful observational technique to image and spectrally measure solar EUV-emitting phenomena.



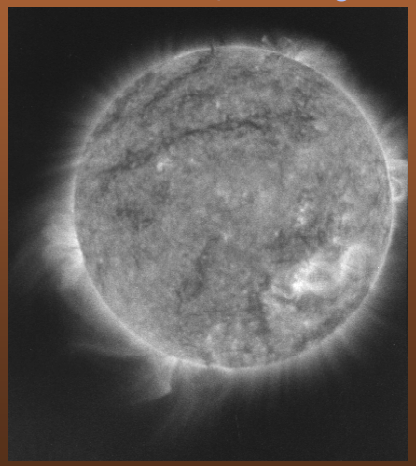
(Underwood et al. 1987, sounding rocket)



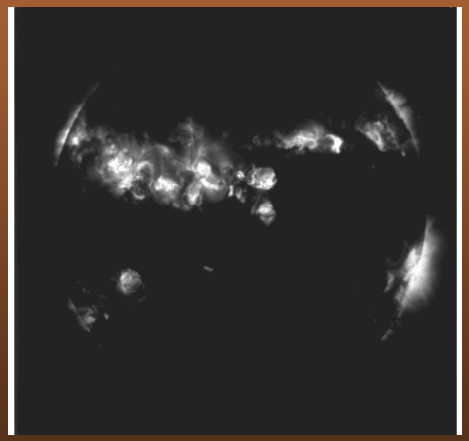
(Walker et al. 1995 , sounding rocket)



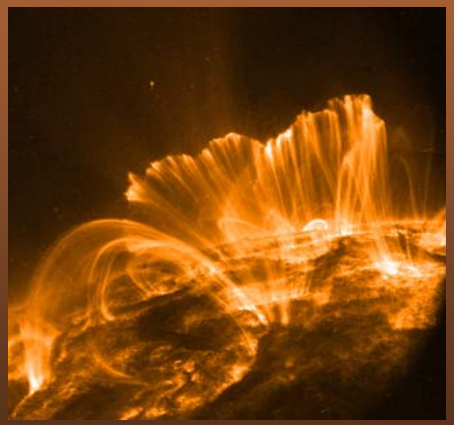
(Delaboudiniere et al. 1996, EIT)



(Walker et al. 1988 , sounding rocket)



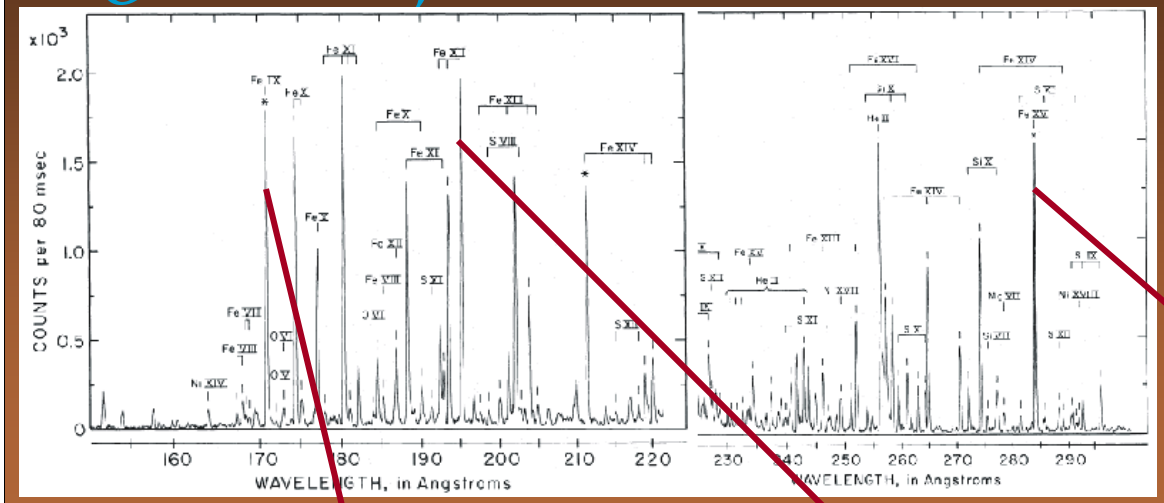
(Golub et al. 1990 , sounding rocket)

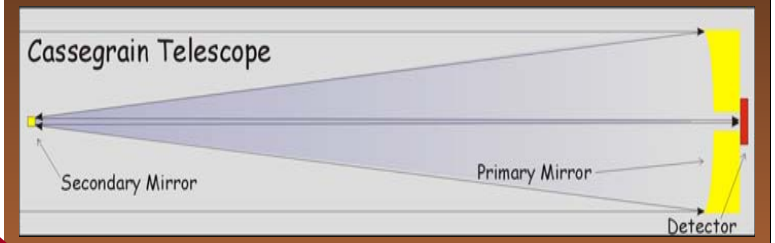


(Title et al. 1998, TRACE)

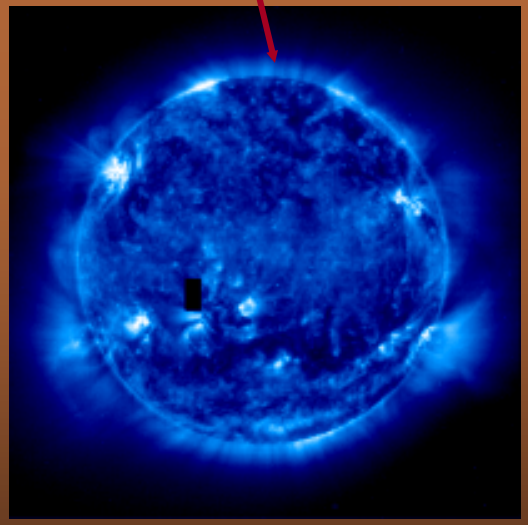
How are Multilayer Optics Used in EUV Solar Physics

Lockheed Martin

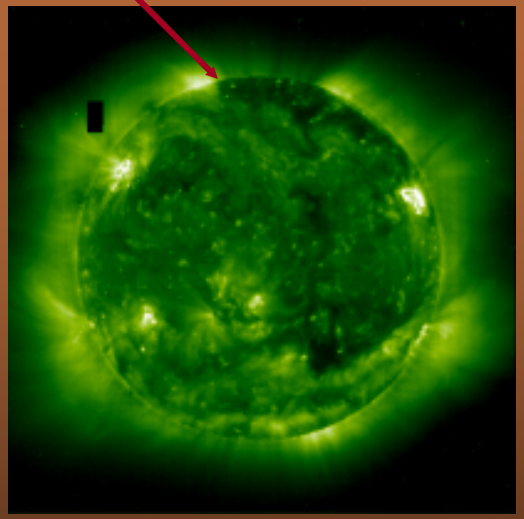




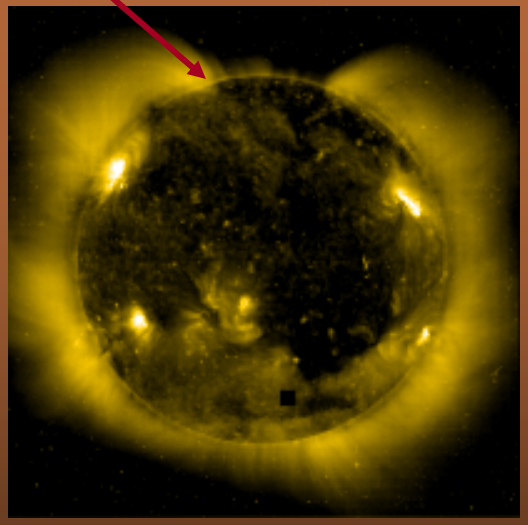
SOHO/EIT, May 1999



Fe IX, λ=17.3 nm
logT=5.9



Fe XII, λ=19.5 nm
logT=6.2



Fe XV, λ=28.4 nm
logT=6.6

The Sun is Magnetic!

Lockheed Martin

Most of the Sun's Variability is caused by Magnetic Fields

- Sunspots are one source of Sun's magnetic field.
- There are references to spots by Chinese astronomers as early as 28 BC.
- Galilieo in 1613 measured solar rotation from the motion of spots.
- Heinrich Schwabe by observing regularly between 1826 and 1843 discovered the cyclic variation in the number of sunspots.
- Edward Maunder noted that sunspots "disappeared" for nearly 70 years - 6 cycles- in the 17th century.
- George Ellery Hale in 1908 discovered that sunspots had magnetic fields.
- Eugene Parker in 1958 predicted a Solar Wind that would drag magnetic field into the Heliosphere.

Faces of Our Sun…

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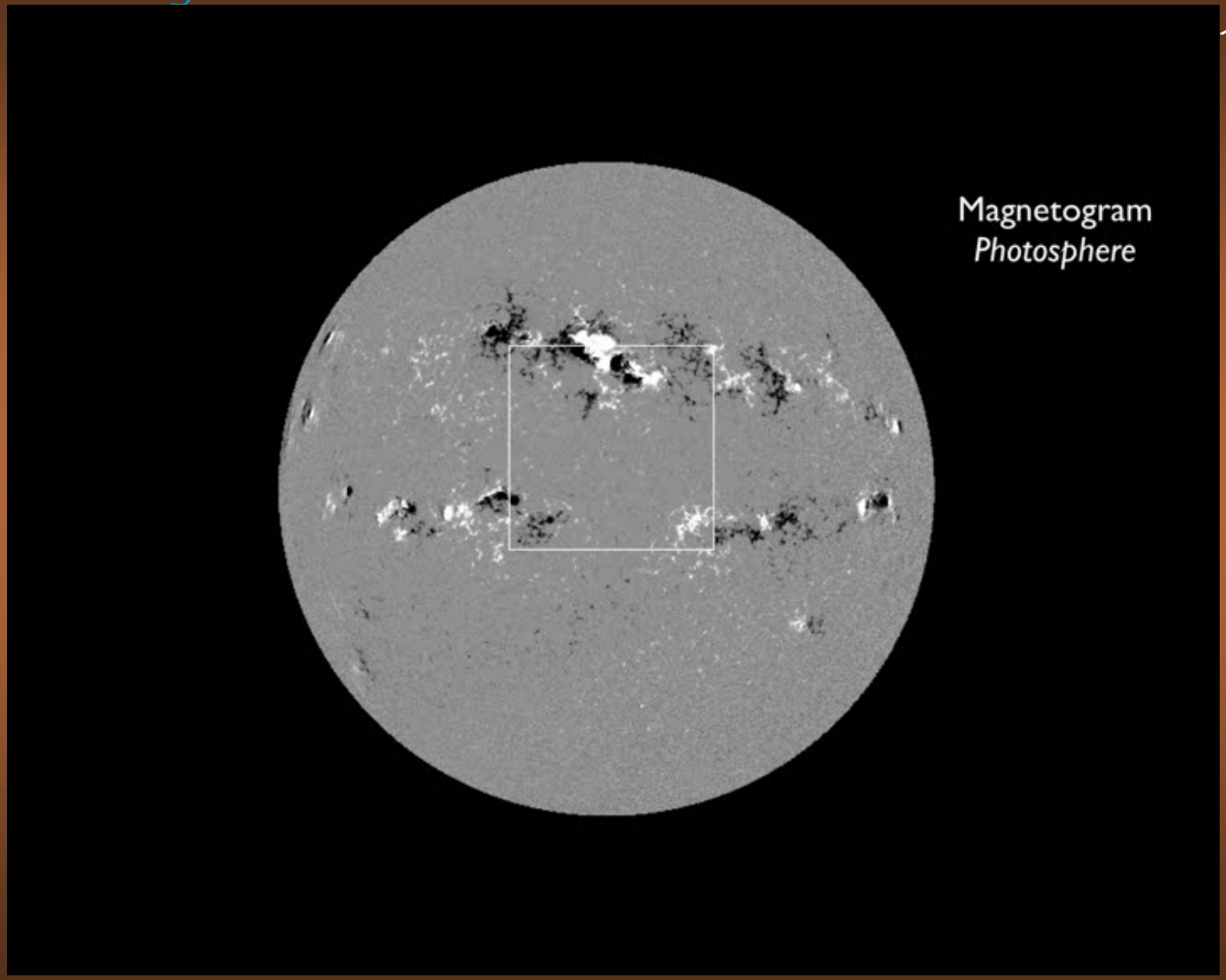

The Evolving EUV Sun…

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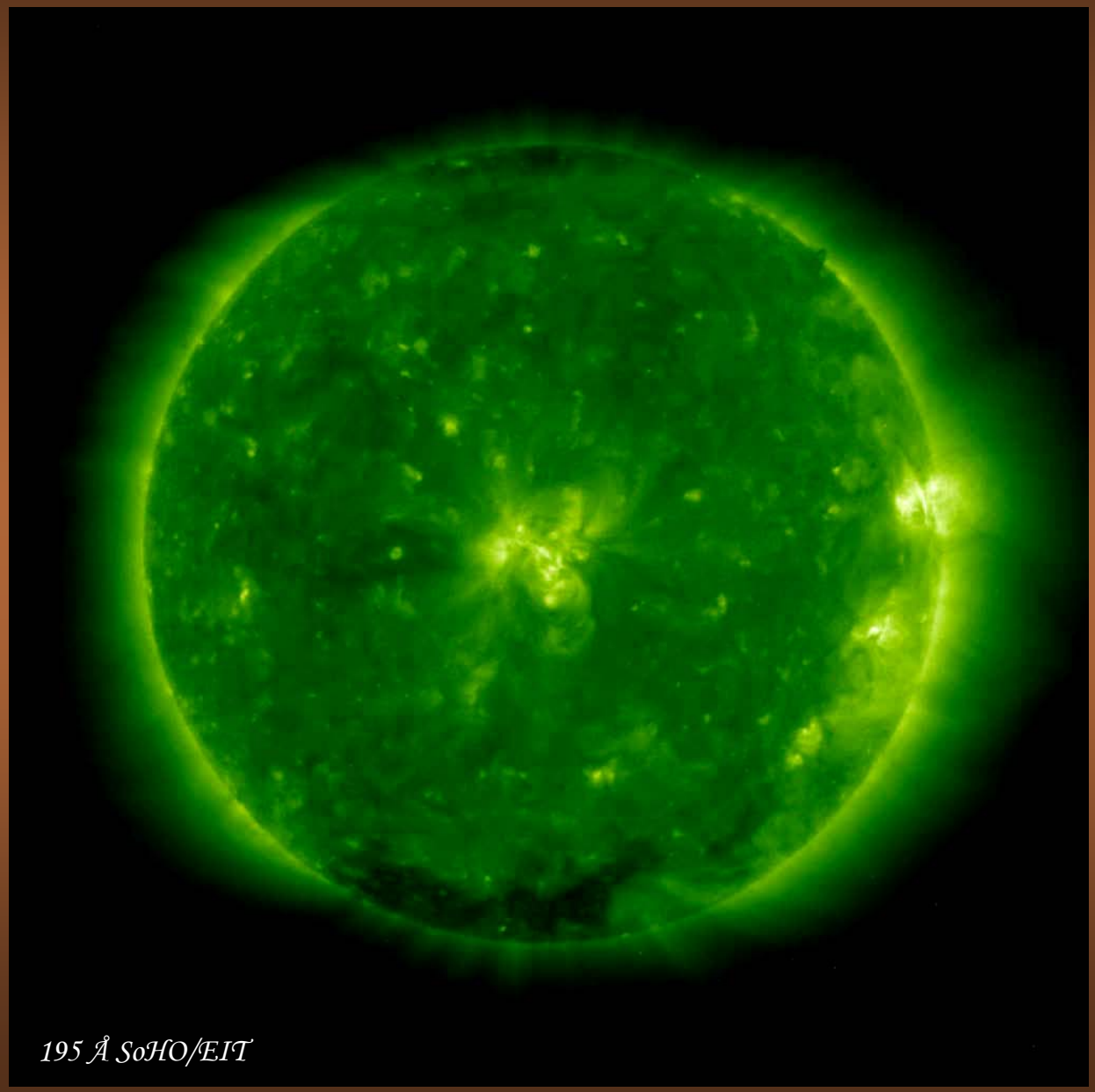


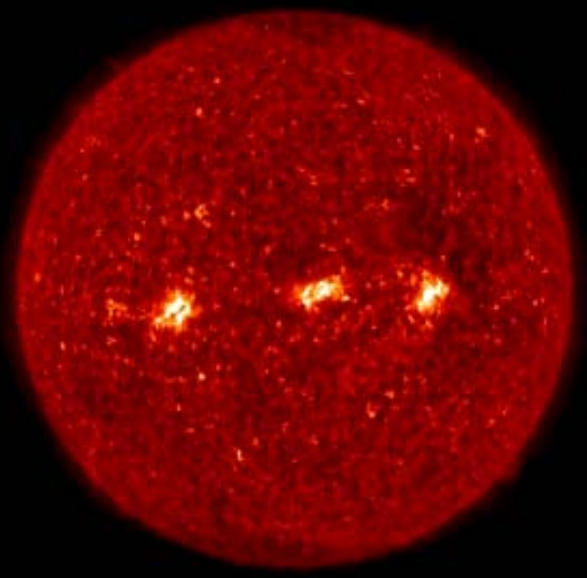
195 Å SoHO/EIT

- The Sun has an 11-year periodicity that shows flux variability at all wavelengths, but most notably in visible, EUV and soft X-rays.

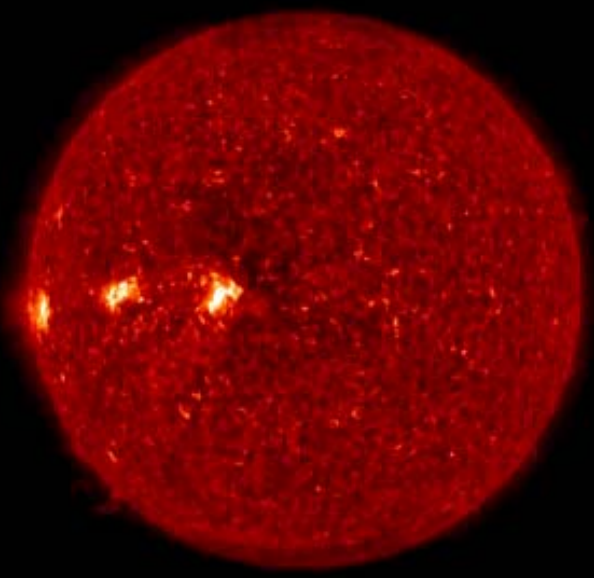
- Over this period the Sun's EUV morphology changes dramatically from being "quiet" to being "active".

Two-Satellite View of the Sun

Lockheed Martin



EUVI on Spacecraft #1
(“STEREO ahead”)

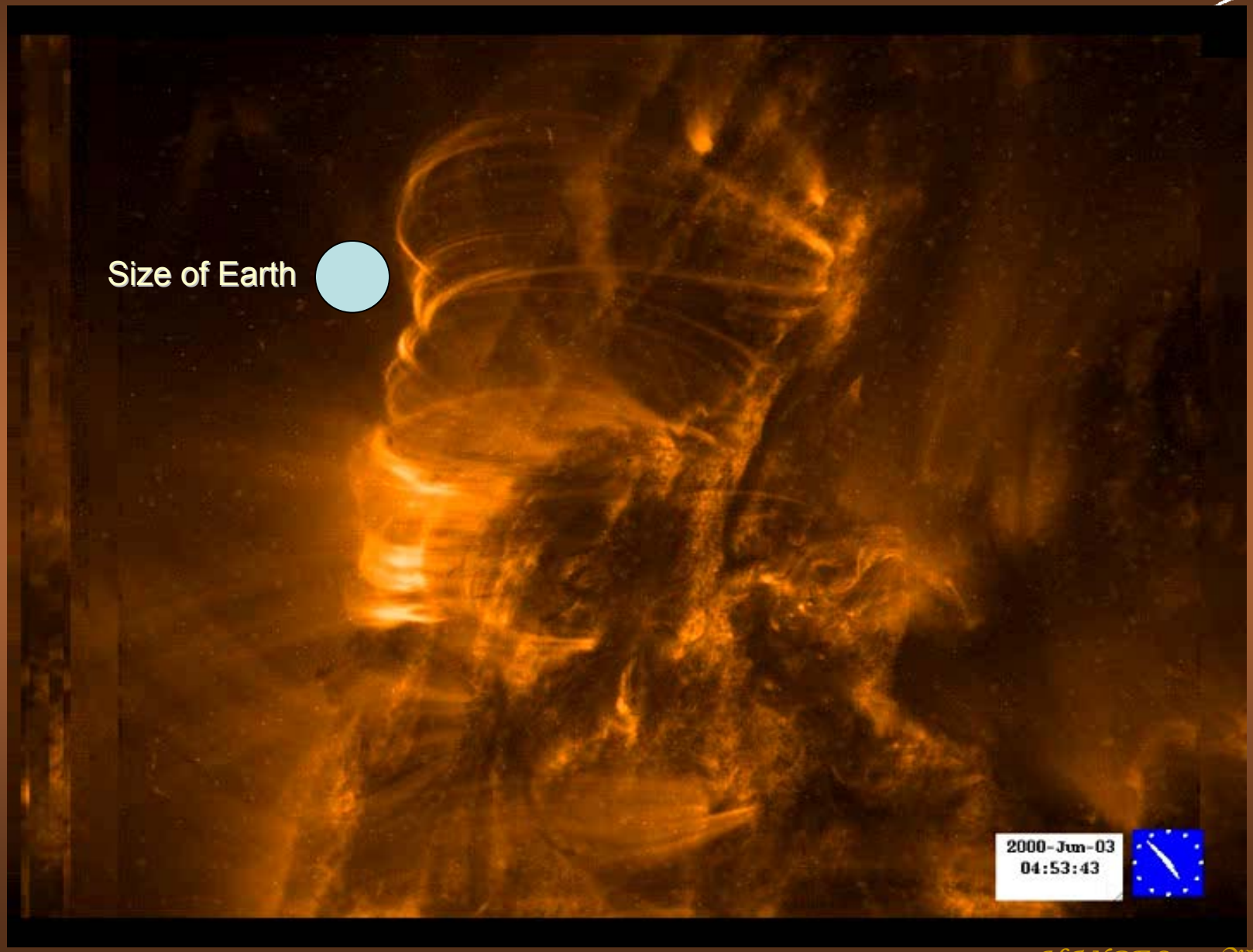


EUVI on Spacecraft #2
(“STEREO behind”)

EUVI on board STEREO spacecrafts

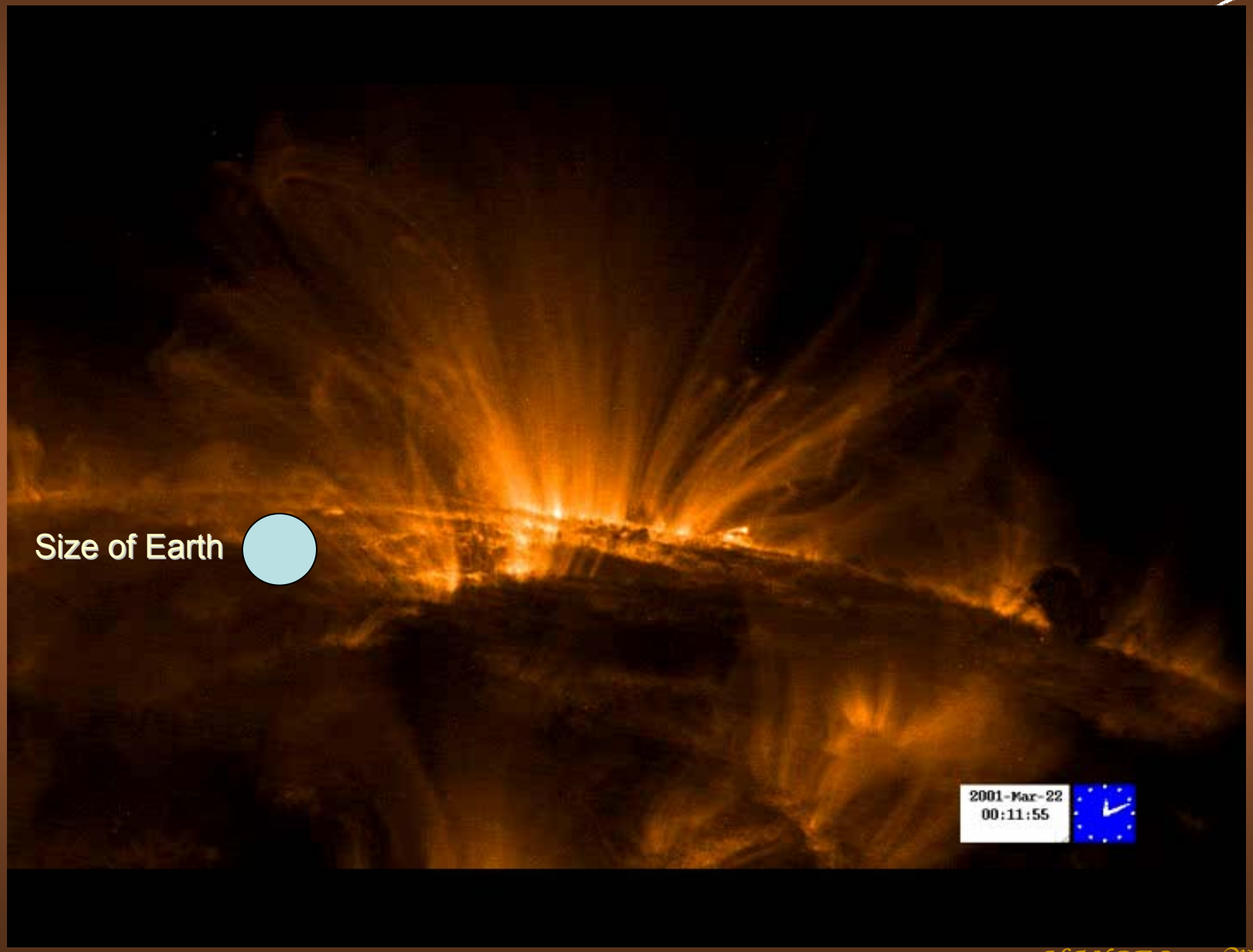
TRACE – 171 Å

Lockheed Martin



TRACE – 171 Å

Lockheed Martin



Hinode Observations at Visible Wavelengths

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The Sun Produces a Wind that Interacts with the Earth

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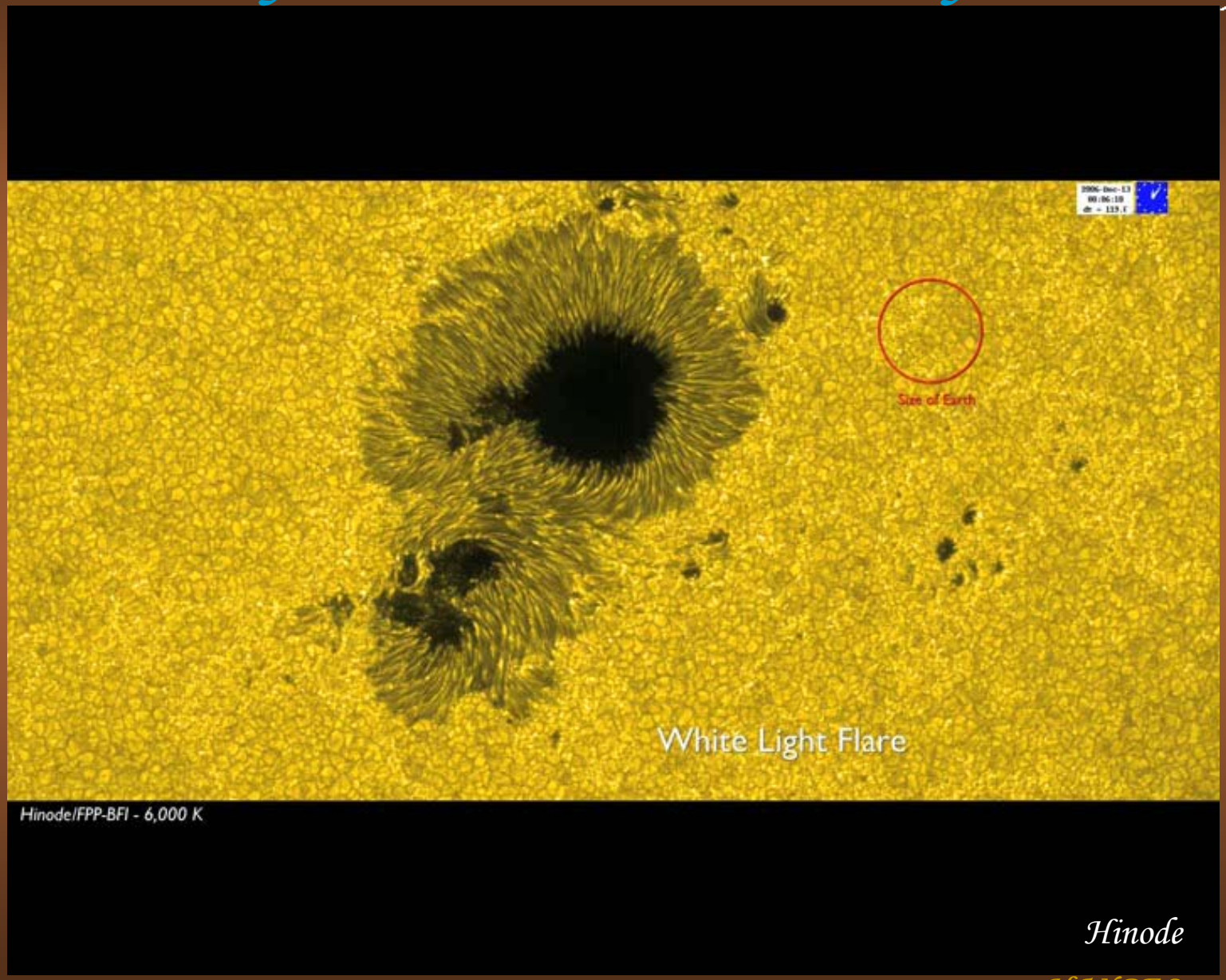
Observations of Flares & CMEs at Varyious λ

Lockheed Martin



Hinode

Coronal Mass Ejections Affect Earth

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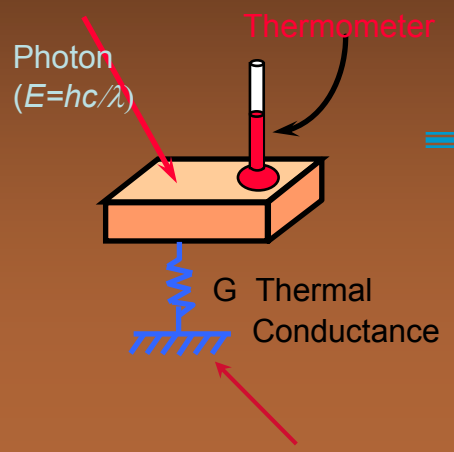
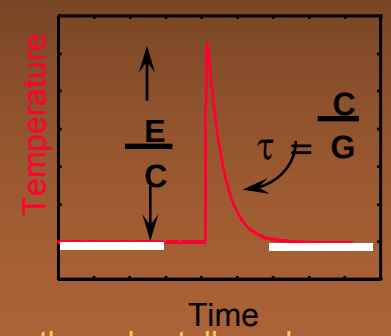
Where's the Future of EUV / Soft X-ray Solar & Astrophysics heading?...

Lockheed Martin

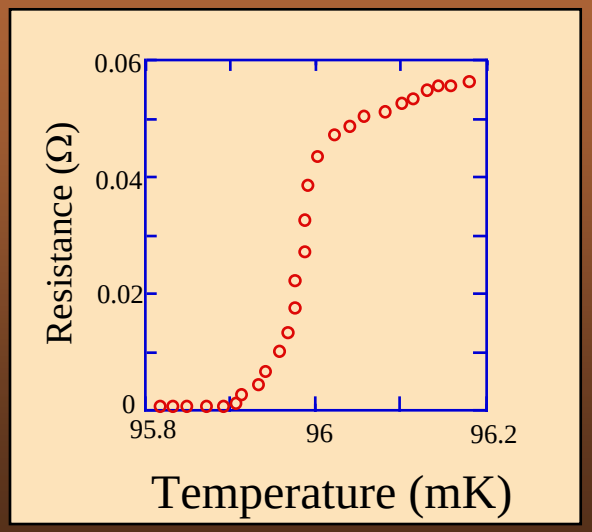


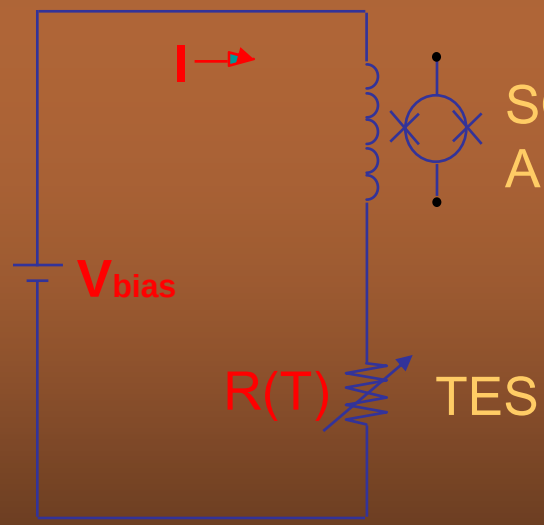


Measuring the pulse tells us how much energy was deposited on the microcalorimeter.

- When a photon is absorbed, the detector heats up and temperature rise is measured. Measuring the pulse tells us how much energy was deposited on the microcalorimeter.

Microcalorimeters are cooled to ~ 100 mK "heat" bath...





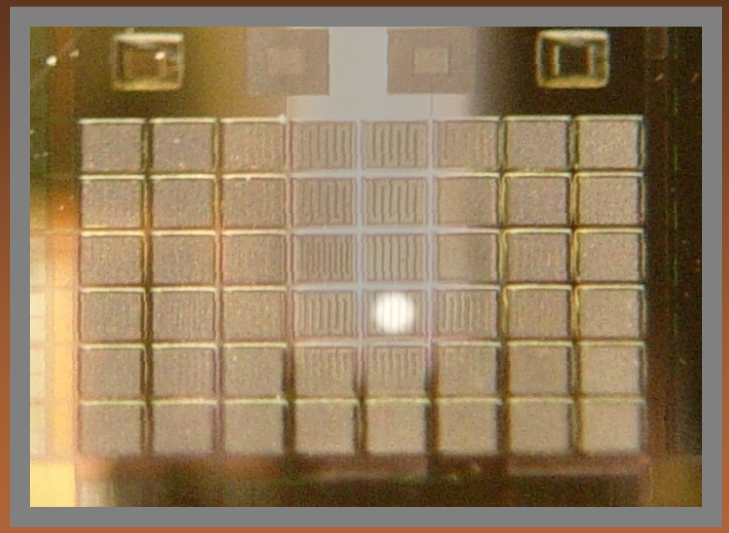
SQUID Amplifier

- Electrothermal Feedback (ETF) self-regulates the TES, creating shorter effective thermal time constant, τ_{eff}

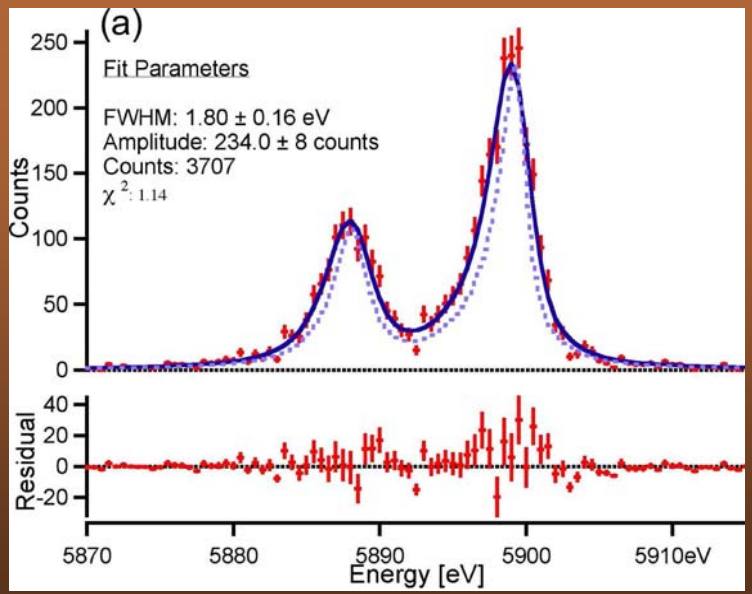
- Several types of low temperature detectors exist but Transition-Edge Sensors (TES) are the LTD *du jour* as they operate at their superconducting transition edge.

TES Performance in Soft X-ray

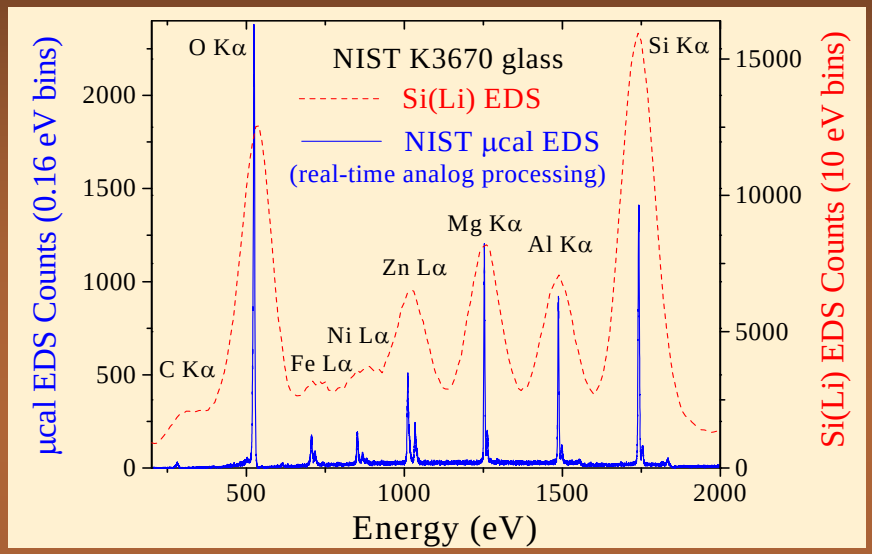
Lockheed Martin



(400 μ x 400 μ pixels, NIST designs)



Best single detector performance, *Bandler et al. 2007*

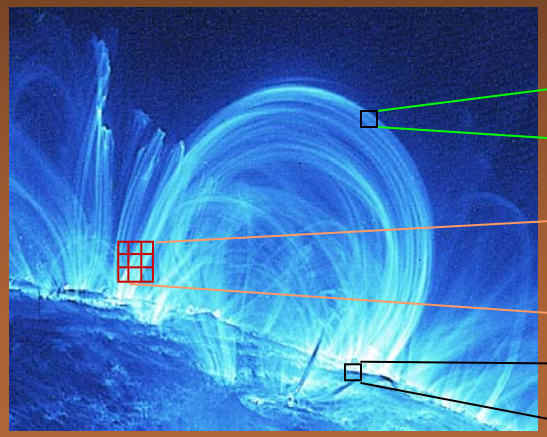


- **TES SPECTROMETER IS SUPERIOR TO ENERGY DISPERSIVE SPECTRO-METERS, BOTH IN ENERGY RESOLUTION AND TIME TO ANALYZE A SAMPLE**

Expected Solar Observations

Lockheed Martin

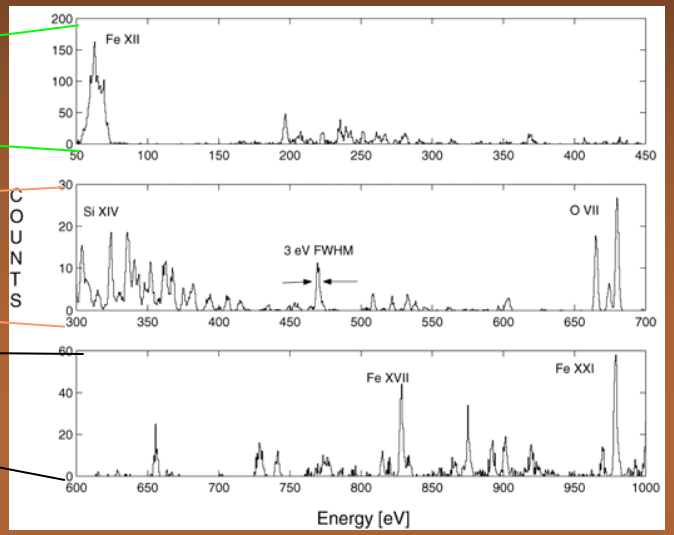
Because TESs have high spectral resolution, an array of TESs will allow us to obtain TRUE spectroheliograms!

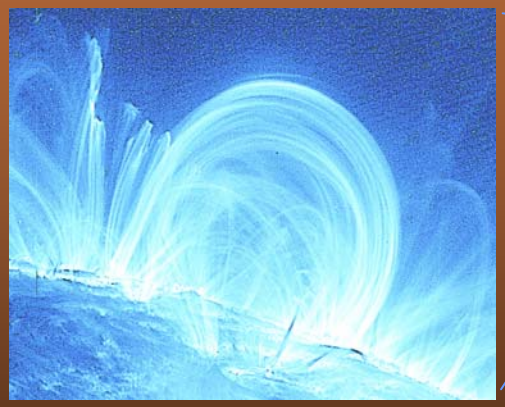


Single TES pixel

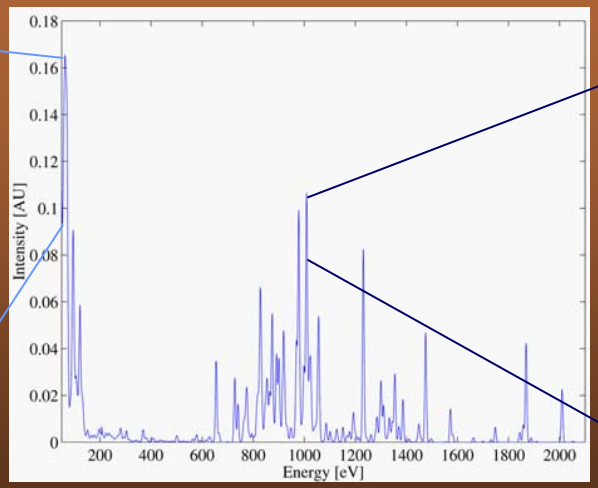
N-pixel average

Single TES pixel





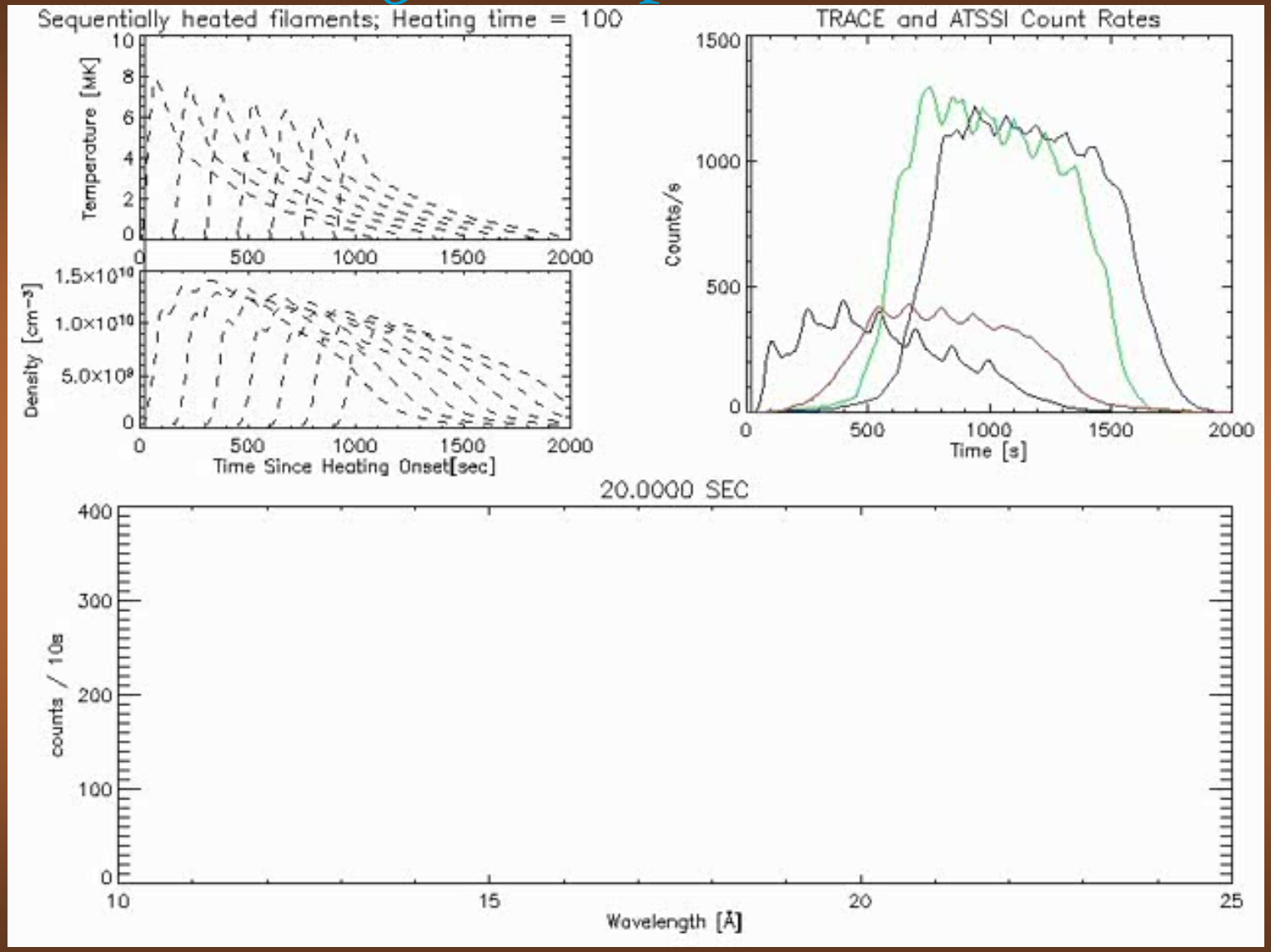
Fe XII



Fe XXI

Other Advantage is Temporal Observations

Lockheed Martin



- The advent of low temperature detectors, particularly TESs, stand to Revolutionize X-ray solar and astrophysics with new findings!

Nano to Galacto… What's the Connection?

Lockheed Martin

- High-resolution imaging of the Cosmos requires large mirrors (> 1 m diameter) with polished surfaces whose figures are extremely smooth < 1 nm.
- EUV spectral optics also require ultra smooth surfaces and the use of multilayer coatings ~ few nm thick.
- Detectors (film previously, having grain sizes ~ 100 nm; and now CCDs) are getting smaller and smaller…, current CCD pixel sizes of ~ few thousand nm (few microns) with densities of over 10 M pixels for a detector array.
- All electronic IC devices in readout systems, controllers and on board computers use circuitry that are ~ nm in scale – in order to increase computing power.
- The scale of the Cosmos that we are probing with the above technologies range from ~ 10^5 m (solar regions) to ~ 10^{21} m (super massive galaxy clusters).
- 114 years after Röntgen's discovery… we are fabricating (nano) structures the size of "X" radiation to probe the far reaches of the cosmic ("galacto") universe.
- Therefore, in order to probe the Universe further - we must continue to develop technologies that get smaller and smaller… to give us more insight in our observations of the Universe…