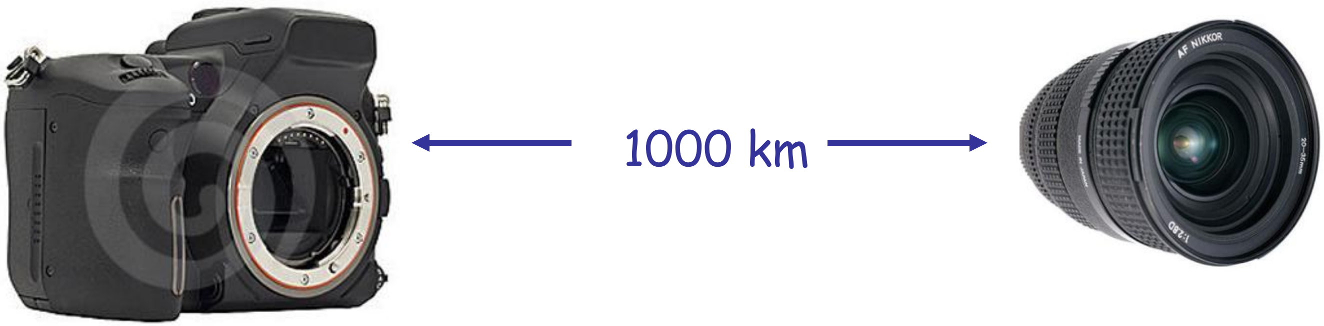
# Very High Resolution X-Ray Telescope Enabled by Formation Flying Between Optics and Detector Spacecraft Separated by Very Large Distance

Paul Gorenstein
Harvard-Smithsonian Center for Astrophysics

Cambridge, MA 02138

Most of the talks presented at this workshop are describing a solution to a problem.




I am describing a problem that I hope fits your solutions.
The problem is a telescope in space with a 1000 km focal Length

# Operating a telescope in space where the lens is 1000 km from the detector

- Line up the source to lens axis with the lens to detector axis within a few centimeters over a distance of ~1000 km.
- Maintain alignment for $10^5$ or more seconds, depth of focus is 10's m
- Change targets
- Re-align new source-lens direction with new lens-detector direction

# X-Ray Astronomy

- 2012 is the 50th anniversary of the discovery of the first cosmic X-ray source, Scorpios-X1 in 1962
- Riccardo Giacconi received the Nobel Prize in physics in 2002 for the discovery plus subsequent work

- X-ray astronomy (0.2-100 keV photons) has developed into a major branch of astronomy, on par with optical and radio astronomy
- Currently 5 focusing X-ray telescope systems are operating in space and 2 more are scheduled for launch in 2014

# X-Ray Emission Processes

Very high temperature regions, T > $10^6$ to $10^8$ K
Charge exchange (e.g. comets encountering solar wind)
High energy particles
  Synchrotron radiation in high magnetic fields
  Inverse Compton up-scattering of lower energy photons

## X-Ray Sources

- Black Holes and neutron stars in compact binary systems
- Neutron stars with high magnetic fields, "magnetars"
- Pulsar wind nebulas
- Giant black holes at the centers of galaxies, e.g. quasars
- Supernova explosions and supernova remnants
- Gamma-ray bursts and their afterglows
- The hot medium in clusters of galaxies
- Stella Coronas and regions of star formation
- Comets and planets in our solar system, by charge exchange, scattering of solar X-rays & fluorescence

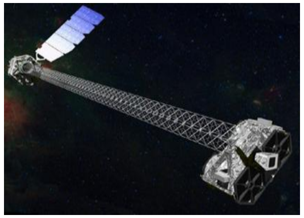
# X-Ray Telescopes Currently Operating in Space.
## All are based upon grazing incidence reflection

Chandra X-Ray Obs. (NASA-MSFC)
High Angular Resolution, 0.5 arc sec HPD

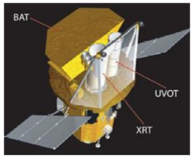
XMM-Newton (ESA),
High Throughput, Ang Res 15 arc sec

Suzaku (JAXA, Japan)
High Throughput, Ang Res 2 arc min

NuSTAR (NASA-JPL)
Hard X-Rays to 80 keV, Ang Res 1 arc min
Extended optical bench



Swift XRT (NASA- GSFC), Ang Res 17 arc sec
Fine soft X-Ray positioning for gamma-ray burst X-ray afterglows providing ID's



# The most important X-ray telescope is the Chandra X-Ray Observatory

Launched in July 1999

General observer facility, 700 proposals/year, ~1/5 selected by peer review,

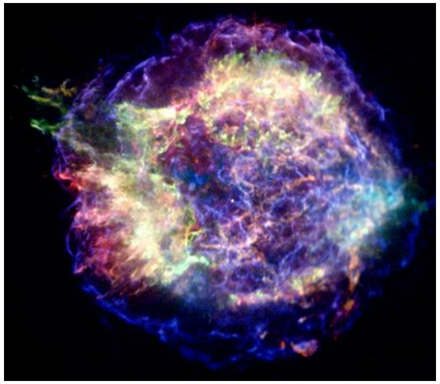
Angular resolution is 0.5 arc seconds (HPD) and effective area is 800 $cm^2$ at 1 keV

Chandra is in a class by itself with respect to angular resolution. 2D res. is 100 times superior to next best, ROSAT (1990-1999)

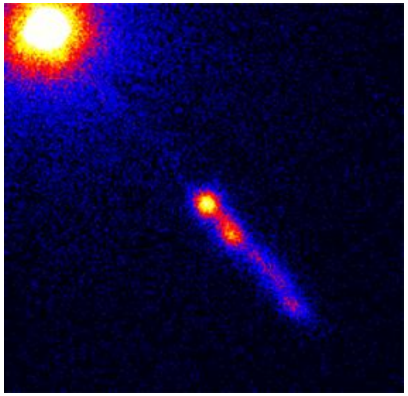
This speaker believes that Chandra's resolution is at or very close to the practical limit of grazing incidence reflection

Better resolution requires a different technology

# X-Ray Images Obtained by the Chandra X-ray Observatory, (chandra.harvard.edu/photo)

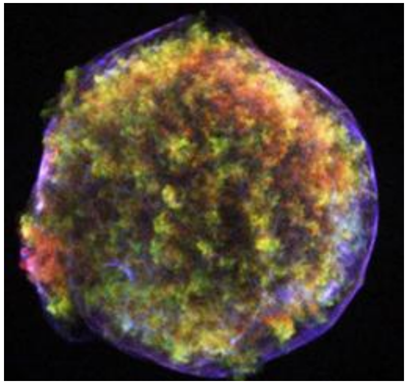


Cas A, supernova circa 1680



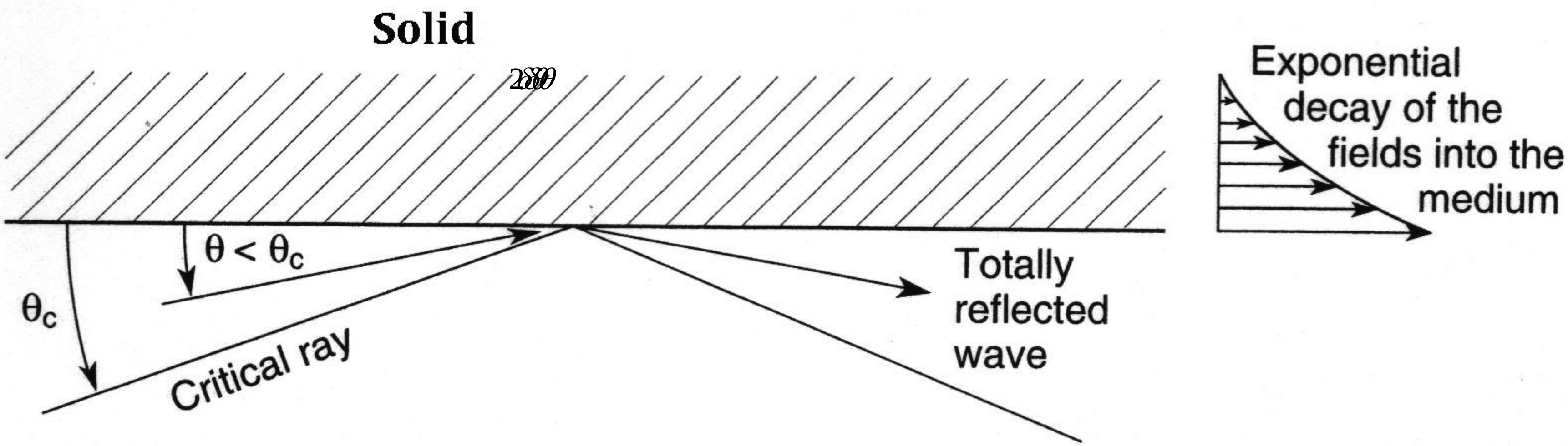
Quasar 3C273 with jet

X-ray image of galaxy cluster (purple) on visible light image



Remnant of 1572 supernova

However, Chandra's angular resolution has probably reached the practical limit of grazing incidence optics



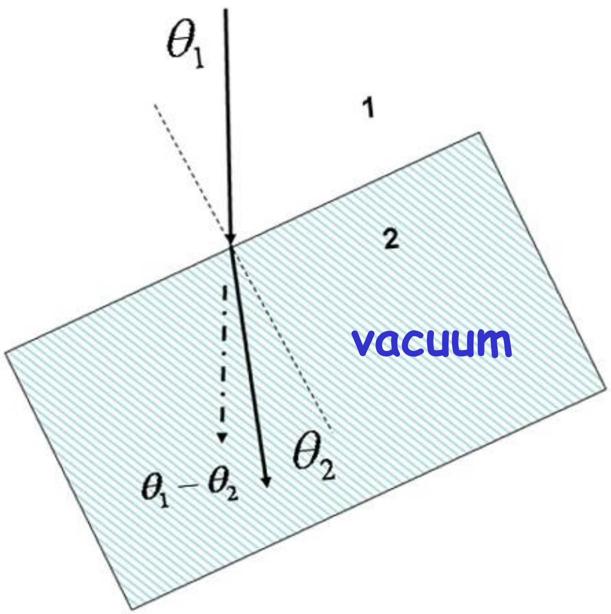

Slope error $\delta\theta$ results in error of $2\delta\theta$ in the direction of the reflected ray.

A new technology not based upon graded incidence reflection is needed to obtain better angular resolution.

# Method with Transmitting Optics

**Medium "1" is the lens material, medium "2" is vacuum**

**The boundary should have been horizontal, i.e. $\theta_1$ = 0**




**Snell's Law**

$$N_1 \cdot Sin(\theta_1) = N_2 \cdot Sin(\theta_2) \quad Sin(\theta_2) = \frac{N_1}{N_2} \cdot Sin(\theta_1)$$

$$Sin(\theta_1) - Sin(\theta_2) = Sin(\theta_1) \cdot \left(1 - \frac{N_1}{N_2}\right)$$

$$N_1 = 1 - \delta \quad N_2 = 1$$

$$Sin(\theta_1) - Sin(\theta_2) = Sin(\theta_1) \cdot \left(1 - \frac{1-\delta}{1}\right)$$

$$Sin(\theta_1) - Sin(\theta_2) = Sin(\theta_1) \cdot \delta$$

$$\delta = 10^{-5}$$

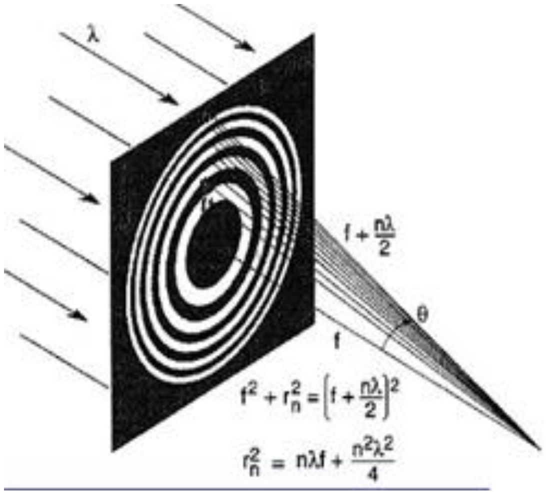
The inclination angle $\theta_1$ is the slope error. The error in direction of the transmitted ray is $10^{-5}$ of $\theta_1 - \theta_2$

- A local slope error of the surface of a reflector results in twice as much error in the direction of a reflected ray

- In comparison, the error in the direction of a transmitted ray is only ~ $10^{-5}$ of the slope error. This is a consequence of the very small difference in the indices of refraction of a vacuum and virtually any material.

- N.B. In the X-ray band the vacuum is always the medium with the higher index of refraction.

# Diffractive and refractive components of transmitting X-ray optics,



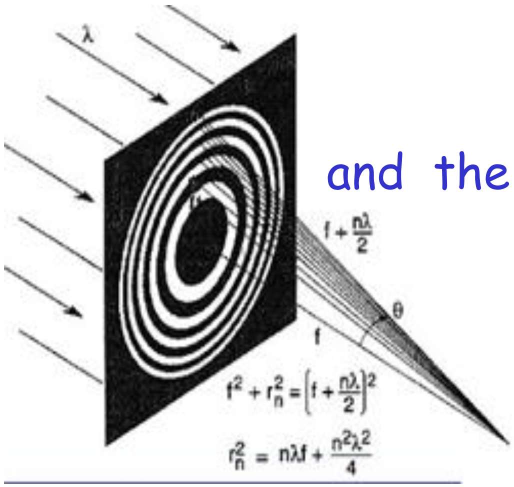

- The diffractive component is a Fresnel zone plate.

- The refractive component is a lens.

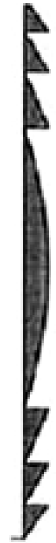
- To reduce absorption it will be a Fresnel lens (will degrade the diffraction limit but to an acceptable level)

# Low Mass per Effective Area of Transmitting X-ray Optics

Both the zone plate




and the (Be) refractive lens

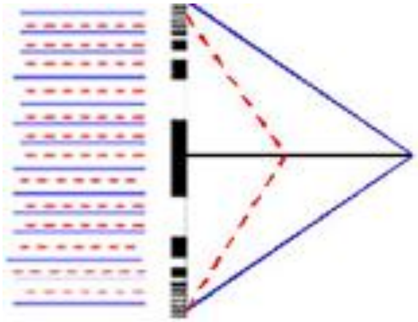


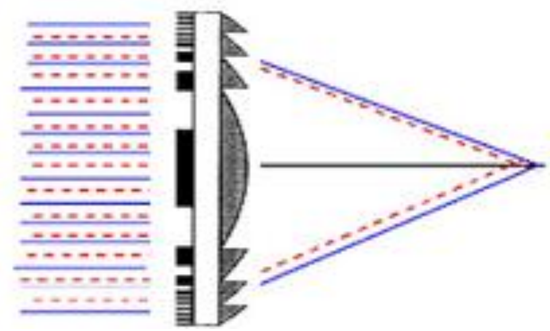
have very low mass/m$^2$ compared to grazing incidence optics. Fabrication should be relatively easy and low cost. Precision machining should be adequate.

# Correcting Chromatic Aberration with FZP/Lens Doublet

Both the zone plate and the refractive lens are highly chromatic.
The focal length of the zone plate varies as the first power of the energy, the focal length of the lens, as the 2nd power.

With the FZP and lens in direct contact, at the energy where the focal length of the lens = -2 x focal length of the FZP, the 1st derivative of the system focal length is zero, i.e. chromatic aberration vanishes

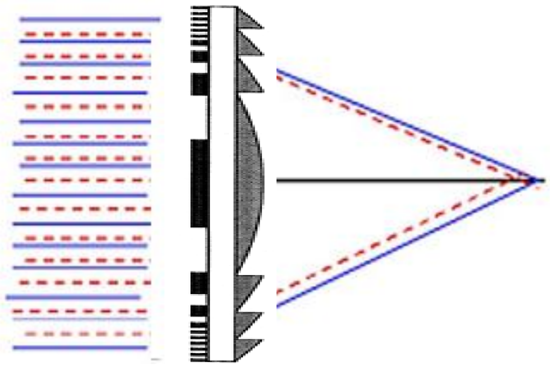




There is a 1.25 keV bandwidth where the mean angular resolution is 1 mili arc second.

# Effective Area and Mass

The efficiency of a phase FZP + refractive lens doublet made of Be is ~0.25 at 6 keV. Most of the rest is either absorbed or remains unfocused in zero order.



- Geometric area of 1.5 m diameter optic is 1.767 $m^2$. It can be divided into 4 sections, each with a bandwidth of 1.2 keV centered upon different energies.

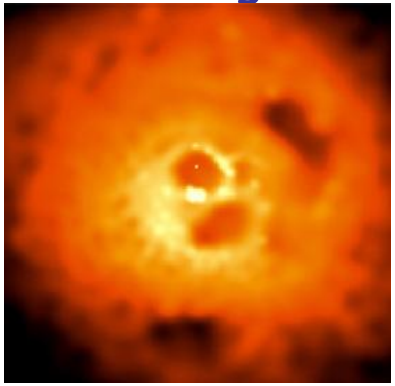
- With efficiency of 0.25, effective area of each of the 4 sections is ~1100 $cm^2$. comparable to the Chandra X-Ray Observatory effective area but only above ~4 keV where the photon flux is smaller than it is at 1 keV.

- Estimated mass of the optics is about 15 kg, mass of Chandra telescope is 1000 kg

- Long focal length results in very small fields of view and high background so sensitivity is not superior to Chandra

# Applications

The diffractive/refractive telescope is not versatile. Very small field of view, ~ 0.5 arc sec, limits it to very small angular diameter objects. However there are many.

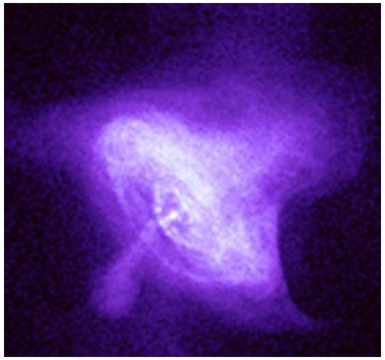


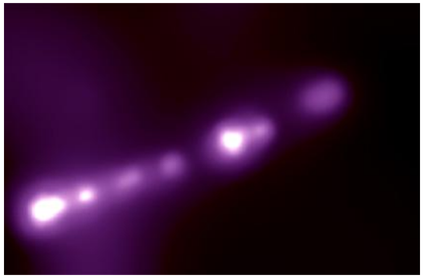
SMBH at center of galaxies

(NGC 1275)

Pulsars

(Crab Nebula)



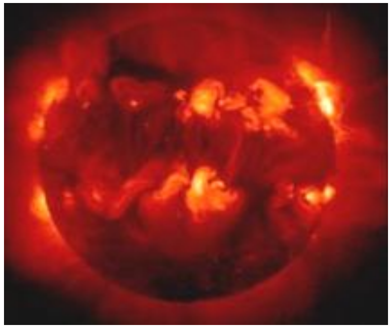


Details of Jets

(M87 Jet)

Stellar Coronas

Sun (Yokoh)



The cosmic images were obtained by the Chandra X-Ray Observatory

# "Formation Flying" Between Optics and Detector Spacecraft

Optics and detector are aboard separate spacecraft (S/C), a focal length, ~1000 km, apart. One S/C's orbit is in ecliptic plane (solar orbit). The other follows using propulsion to overcome gravity gradient.

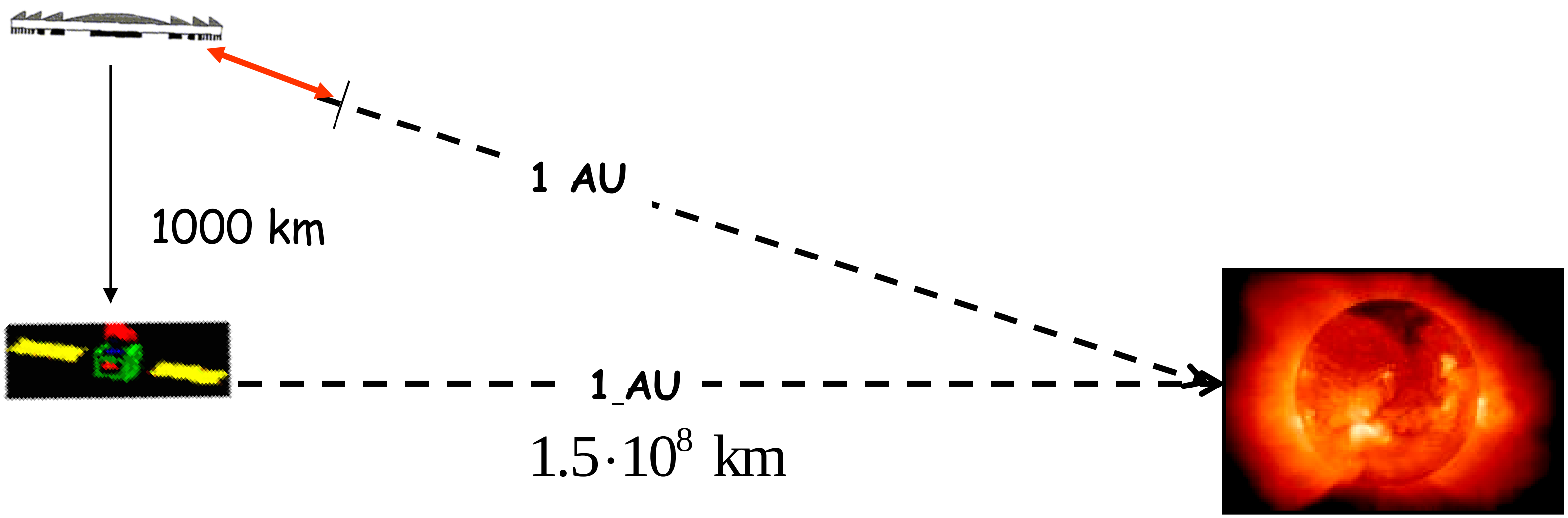
Their mass is unknown at this time but should be < 1 ton each

**Propulsion is needed to:**

- Transport the optics and detector S/C's from LEO to low gravity gradient orbit
- Align detector to optics direction with optics to source direction within few cm in lateral directions and with 10 m along the axial direction
- Point the telescope, which acts like thin lens, high pointing accuracy not required
- Change targets by repositioning either the optics or detector spacecraft
- Exposure times will be the order of $10^5$ seconds, mission duration, $2 \times 10^8$ sec
- Observing efficiency will improve if there are two spacecraft with optics (or detectors), one observes while the other proceeds to the next target

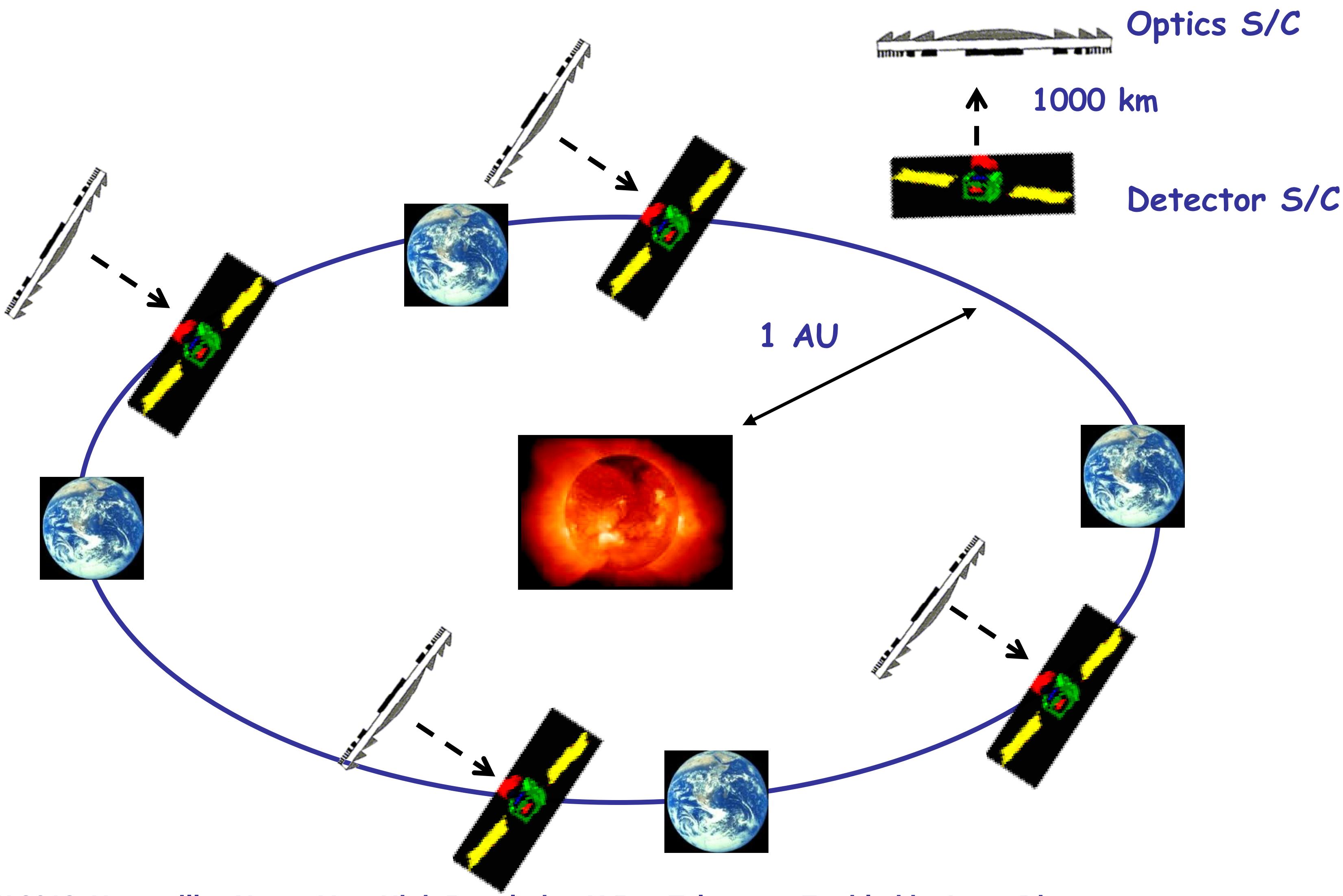
**Hopefully one or more of the propulsion systems described at this workshop will be able to satisfy these requirements for at least four years of observing.**

The detector S/C is in a solar orbit along the ecliptic plan pointed to target. Engines on one optics S/C are counteracting the gravity gradient to remain $10^3$ km above detector S/C along source direction. Second optics S/C is on way to next target position.




Changing targets by moving 1 ton optics S/C 1000 km in $10^5$ seconds requires force of ~ 0.4 mN

# Detector S/C in solar orbit, Optics S/C follows in Powered Trajectory

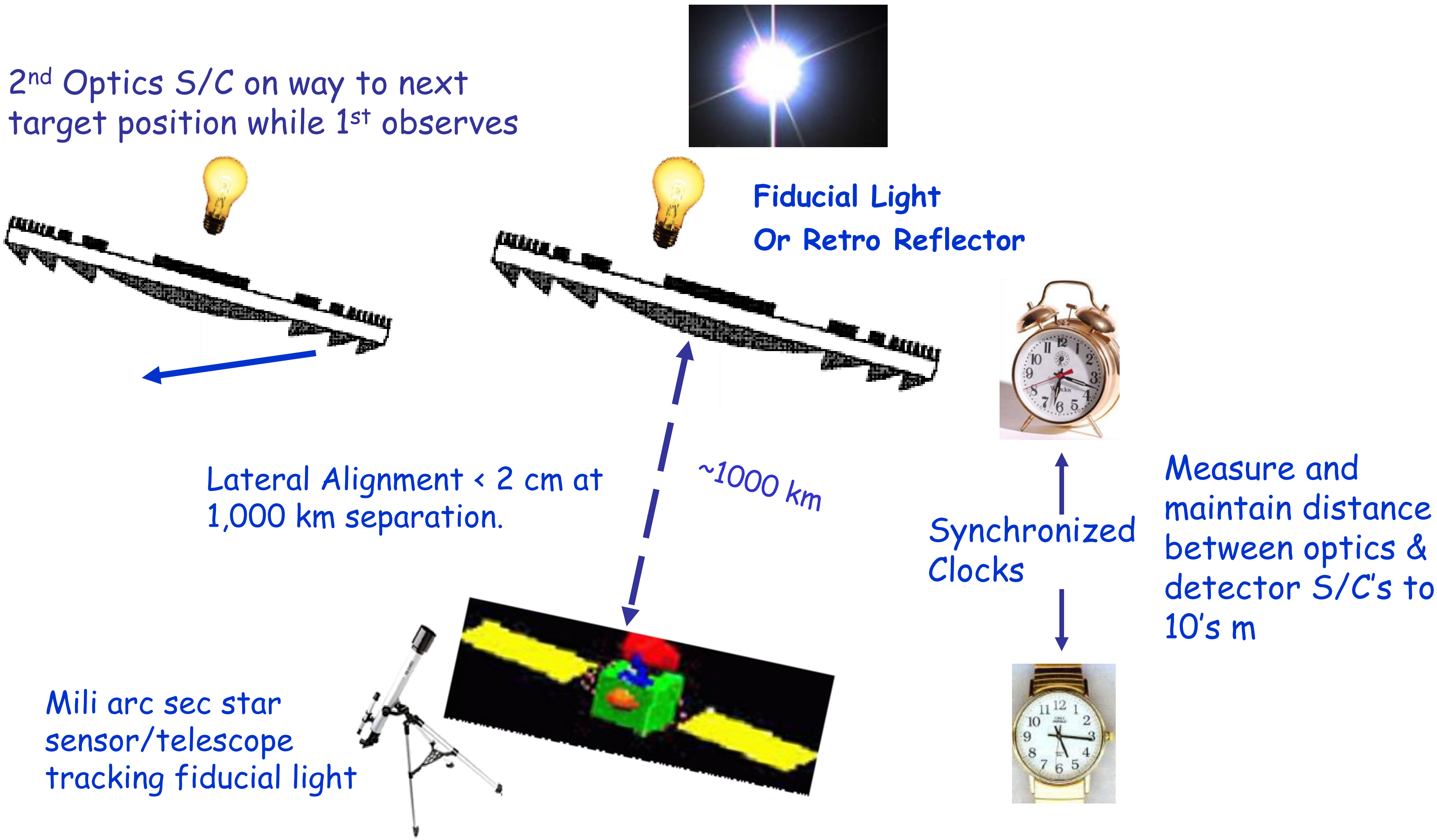


# Propulsion Requirements
# Low, long duration forces

| Task | Active S/C | Initial Force[1] | Duration (sec) |
|---|---|---|---|
| Point Detector/SC to Target | Detector | Small. Change in pointing direction Minimal propellant consumption | 200 ? |
| Optics S/C navigates to point 1000 km above detector along target direction | Optics | 0.4 mN for 1 ton S/C<br>Most of the mass of optics S/C is propellant | $10^5$ |
| Observing<br>Optics points to target | Optics | $80\ \mu N$<br>To counter gravity gradient force upon 1 ton optics S/C | $10^5$ |

[1]Estimates with rocket equation ignored. Requires verification.
Forces will diminish as propellant is consumed, reducing mass of optics S/C

# Station Keeping Along Very Large Distance



# Very Long Focal Length: Problems and Solutions

The extremely long focal lengths required by the system, ~$10^3$ km is the source of several problems. They are:

- **Aligning the detector with the optics to an accuracy of a few cm:** By bore sighting on bright star to mili arc sec accuracy detector S/C can align the detector- optics direction with that of detector-target direction to a few cm. Distance between optics and detector is less critical ~10's meters. Time of arrival of signals from optics S/C to detector S/C should provide sufficient accuracy. Pointing accuracy is not an issue. Optics are a thin lens.
- **Changing targets:** Time required to change targets is as long or longer than the length of the observation. Two detector or two optics spacecraft are needed. While one observes a target, a second spacecraft is navigating with ion engines to the next target.
- **Large focal plane scale results in high background:** A grazing incidence telescope (ellipse + hyperbola) can reduce focal plane scale plus the background by a large factor at a loss in area of about a factor of 3 and some loss of resolution by re-imaging the focal plane of the diff-ref telescope onto a smaller detector.
- **Large focal plane scale results in small field of view** : Field of view is inherently large in angular coverage with little loss of resolution off-axis. However, it is limited by the size of the detector. Detector can perform s raster scan of the field without changing distance to optics. Employ very large, few meters, format CCD or CMOS arrays

## Summary and Conclusions

- ❖With 0.5 arc sec resolution the Chandra X-Ray Observatory is already at or is very close to the practical limit of grazing incidence X-ray optics.
- ❖Active figure control of segmented substrates is not likely to improve upon Chandra's resolution. There are too many substrates to configure and align.
- ❖Diffractive-refractive optics that transmit X-rays seems to be capable of attaining mili arc second resolution with optics that are lightweight and low cost.
- ❖However the difficulty of constructing high resolution, grazing incidence optics is replaced by difficulty in mission operations, namely "formation flying" between optics and detector spacecraft separated by ~1000 km.
- ❖At least one of the two spacecraft has to be equipped with propulsion engines to reach its target, remain on target by countering gravity gradient forces, and change targets.
- ❖Two optics (or detector) spacecraft with first observing while second navigates to new target position during an exposure will double the observing efficiency.
- ❖The experience gained in formation flying with diffractive-refractive optics is directly applicable to the ultimate in high angular resolution x-ray astronomy, namely the much more challenging X-ray interferometry.

# Request for Comments

Please send comments to:
Paul Gorenstein
Harvard-Smithsonian Center for Astrophysics
60 Garden Street, MS-4
Cambridge, MA 02138

**e-mail: pgorenstein@cfa.harvard.edu**

**Phone: 617-495-7250**
**Fax : 617-495-7356**

- Where does this concept stand with respect to current technology?
- Possible Now? Any current project addressing similar situation?
- Possible in future with progress expected in current projects? Concept flawed?
- Length of both exposure time and time needed to go to new target is $10^5$ sec.
- Do estimates of forces needed to counteract gravity gradient at 1 AU upon 1 ton S/C over $10^3$ km distance (80 microN) and navigate to new target, (40 mN) seem correct?
- How much and what types of engine and propellant needed for 5 year mission with 1 detector and two optics S/C's. Radioactive isotope power source is OK for optics S/C.

The 2D angular resolution of the Chandra X-Ray Observatory or pixel size is 0.25 arc $sec^2$

ROSAT (1990-1999) had the 2nd best angular resolution at 25 arc $sec^2$, **a factor of 100 worse**