The X-ray Navigation Program at NRL

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A Discussion of how NRL's development of X-ray navigation occurred within the broader context of its program in UV, X-ray and Gamma-ray Astronomy

Two Themes

The NRL X-ray navigation has been characterized by exploration of two major themes

1. **Pulsars** of all types; also, other rapid variability signatures
2. **Eclipses and occultations** – giving sharp edges and defining long straight lines in space; other useful high-contrast temporal modulation

Both had roots in the 1960s

Since so many other talks cover pulsars, this one will expand somewhat on the second theme

Take a look at the various paths that have been explored over the years.
Mostly chronological order, tracking both themes, with references.

Origins

Early Sounding Rocket Work

- **NRL's space research entered its rocket phase with Herbert Friedman's sounding rocket flights in the late 1940s. X-rays from the Sun were discovered**

- Proportional counter systems flown in the 1960s established early sketch of the X-ray sky. Source variability immediately became evident.
- **NRL conducted a search for a neutron star in the Crab Nebula *using a lunar occultation* before discovery of pulsars and without X-ray optics .**
- **After pulsars were found in radio and X-rays, the first X-ray pulsar was found by NRL, the Crab Pulsar.**

First theme starts here

Fritz *et al*. Science 169, 366 (1969)

***NRL and GPS :** Roger Easton, the "Father of GPS," was undertaking Project Vanguard and developments leading to GPS concept during years 1955-64. Use of periodic signals as navigation aids was a longstanding NRL interest.*

Second Theme Starts Here

7 July 1964 Crab Occultation Flight

At that early epoch, near the dawn of X-ray astronomy, a lunar occultation was the best way to achieve fine angular resolution

Scientific **goal** was to determine whether the X-ray source (then known for only a year) was a **point source** (Neutron Star) or **extended** (the Nebula)

Extent of Crab Nebula was known in other wavelengths but not X-rays. An X-ray source extended of order an arc-minute would disappear gradually as the Moon passed between Earth and the Nebula, but a point source would show an abrupt drop at ingress.

There was speculation favoring each possible outcome.

Key participants then at NRL were Friedman, Chubb, Byram, Bowyer, Fritz

Ted Byram ran the launch, using a sidereal clock!

Classic experiment -- with *perfect* launch timing -- but severely limited by detector areas

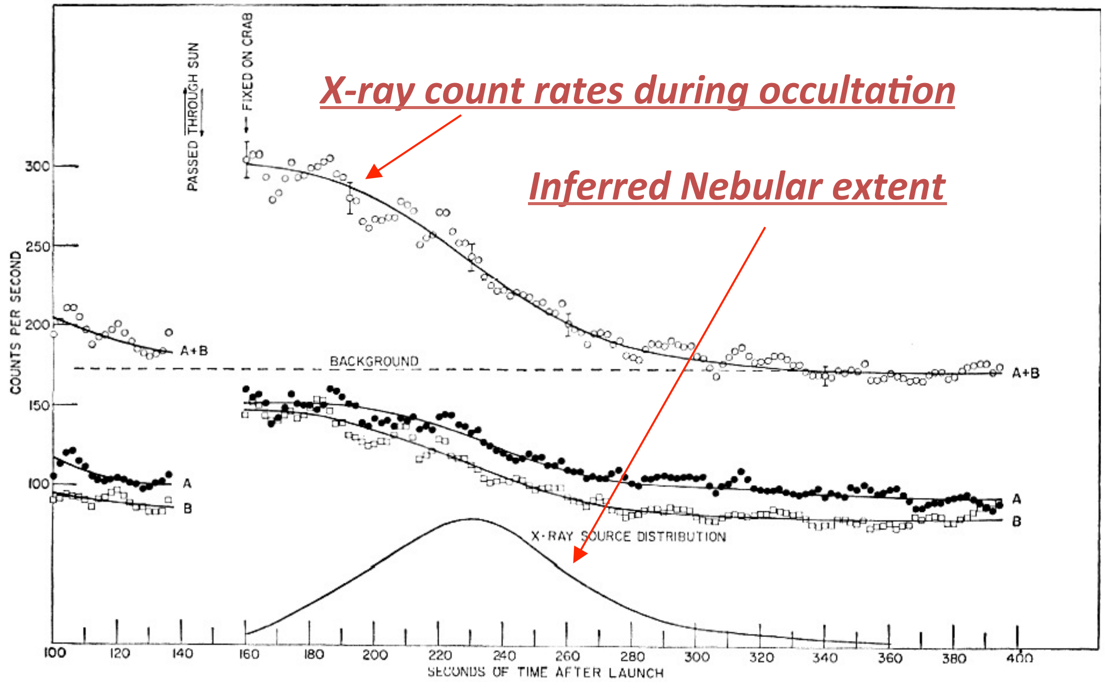


Fig. 2. Variation of the observed x-ray flux during the course of flight of 7 July 1964. The Mylar windows of counters A and B were 1 mil and ¼ mil thick, respectively. Counting rates were computed from the time required for a fixed count of 768 in each counter. A running mean is plotted at 2-second intervals. The x-ray source distribution is the derivative of the *A* and *B* curve.

13 NOVEMBER 1964 913

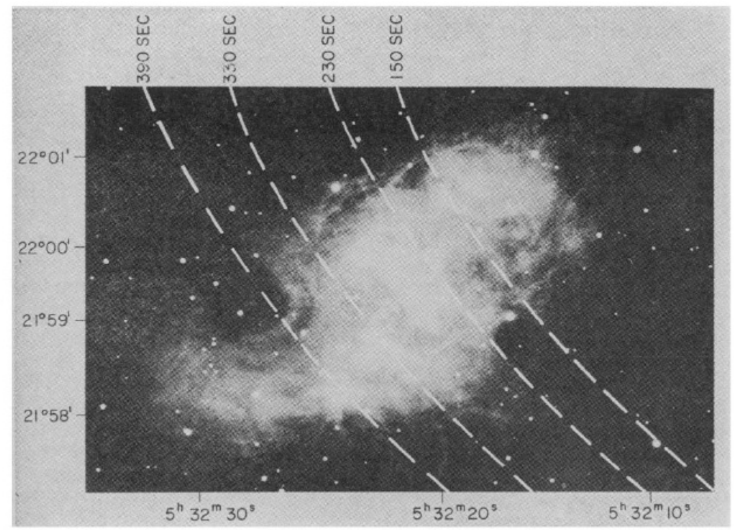


Fig. 3. Progress of the occultation of the Crab Nebula measured in seconds of time after launch of the rocket from White Sands missile range. The dashed curves represent the positions of the edge of the moon. A maximum rate of decrease in x-ray flux was observed at about 230 seconds.

Apparent advance rate of limb ~ 1 arcsec/s

Bowyer, Byram, Chubb, and Friedman, Science 152,66 (1964)

Launch time had to consider Nebula centroid and location of lunar shadow, not on ground but *on rocket trajectory at altitude*

Detectors were two Geiger counters, each 114 cm^2 frontal area

(Projected) Nebular brightness distribution from derivative of count history.

Registered on sky (w.r.t Nebula) using lunar ephemeris and rocket trajectory

Pulsars, and also *Alternatives*

In the early 1970s it was clear neutron stars were X-ray sources.

- **Periodicities were known (Crab, since 1969; Her X-1, Cen X-3, etc.)**
- **Timing noise was recognized and being characterized**
- **Pulsars were regarded as one option among others for timing and navigation**

In the era of sounding rockets, the black hole source Cygnus X-1 had been found variable, showing *aperiodic* variability, over decades in timescale.

- Subsequent analysis over many years revealed variability extending to shorter and shorter timescales, down to milliseconds.
- **This is potentially useful for time transfer or for relative navigation**

HEAO A-1 found first unpulsed eclipsing low-mass X-ray binary (LMXB), the system now known as X 1658-298 (see next slide).

Thus, not just pulsars but many options.

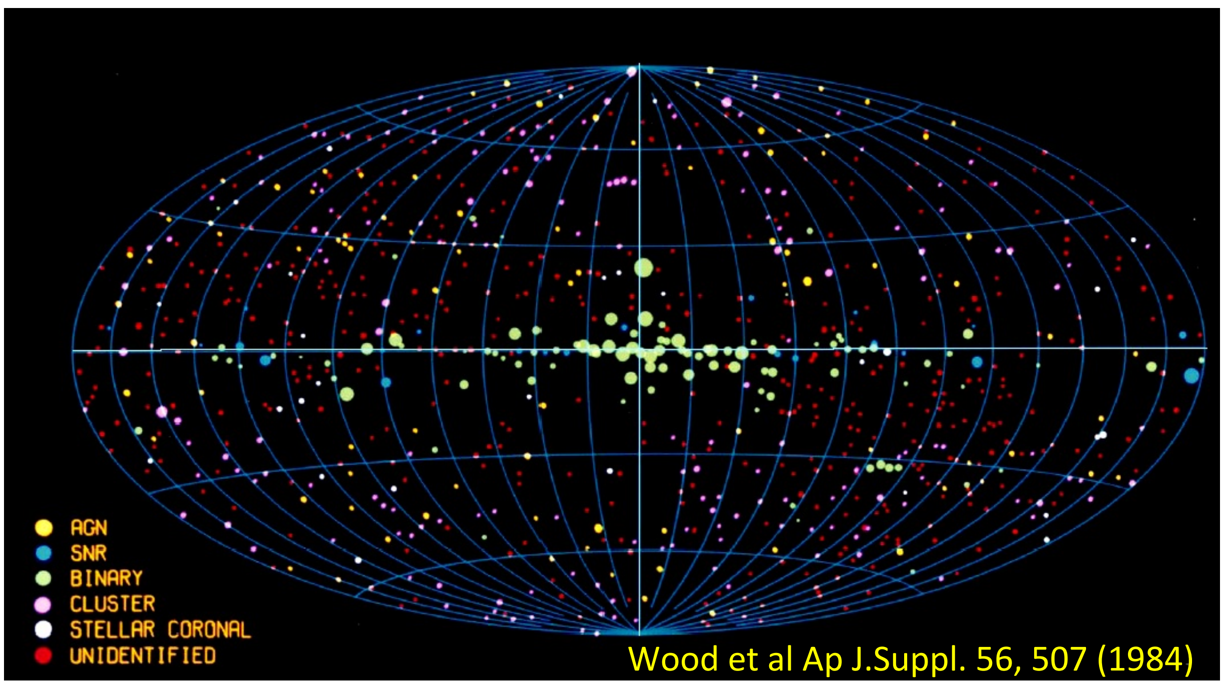
Millisecond pulsars were not yet known to be X-ray sources

(in fact B1937+21 was found in radio only in 1982)

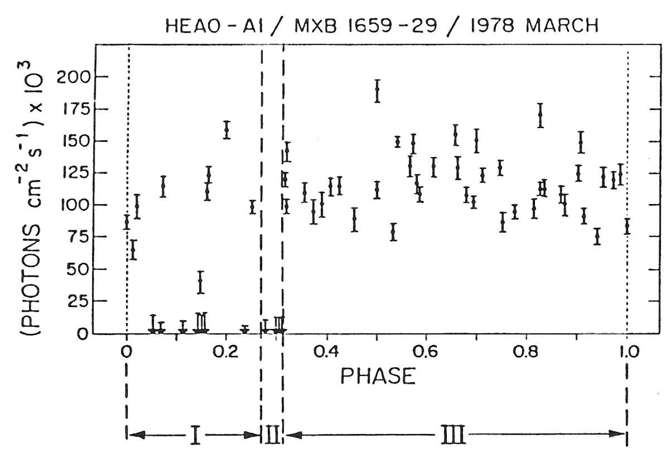
In early development of X-ray program, NRL researchers always asked: Why perform tasks in X-rays rather than, say, optical? Answers included (i) detector system options, (ii) distinctive signatures of X-ray sources (e.g., Crab, Cyg X-1), and (iii) short wavelengths, i.e., minimal diffraction.

HEAO-1 (1977-79)

- **X-ray source classes were surveyed through 1970s, 80s.**
  - **Catalogs are basis for X-ray star-trackers, i.e., X-ray attitude**
  - **But it was being learned the X-ray sky has almost no steady point sources**
- **MXB 1659-29 eclipses discovered using HEAO-1**
- Cominsky and Wood, Ap. J. 283, 765 (1984); also Ap. J. 337,485 (1989)
- **Eclipses provided a different kind of periodic signal, infrequent but with a distinctive, sharp edge. It seemed to have promise for application**
- **The precision of this celestial clock was initially unknown, but timescale for evolution of the orbit was known to be long, of order few x 10^8 yr. This and another eclipsing system, Exo 0748-676, were monitored for years.**



Wood et al Ap J.Suppl. 56, 507 (1984)



Mid-1980s:

XLA Concept leading to USA Mission

- **After end of HEAO-1 mission (1979), NRL increasingly specialized in study of X-ray source variability.**
- One idea from the 1980s was a 100 m^2 array called the X-ray Large Array (XLA), which had a NASA study but never flew. *It was similar in emphasis to LOFT, currently proposed to ESA.* (For XLA retrospective see Wood, Wolff and Ray in *X-ray Timing 2003*, Kaaret, Lamb, and Swank, *Eds*.)

  1980s were when X-ray navigation got interesting; XLA was key

- **XLA's legacy** was a dream of **large exposure (area x time product)** on sources. **This led to the Unconventional Stellar Aspect Experiment on the *ARGOS* satellite**.

Before getting to USA, will look at some

related ideas involving large exposure and occultations

Mid-1980s

Occultations and High Precision --
for Angular Resolution or Position

Theoretical understanding of X-ray source classes predicts many interesting phenomena on scales from arcseconds down to micro-arcseconds –

stellar coronae, binaries, AGN, blazar jets, …

A large array combined with occultation can access intermediate (m.a.s.) scales

XLA would have area large enough to explore milliarcsecond domain

The Moon alone gives access to Ecliptic latitudes ± 6° over 9 years

– 10.4% of full sky Crab, 3C273 and various other sources

This is a science goal, not astronautics, ***but it leads directly back to astronautics;***

An artificial occultor in high orbit would work to increase sky access to 4π (100%)

- Wood and Breakwell (*Acta Astronautica*, *15*,9 (1987)) considered for use with large arrays in LEO
- High orbit knowledge/control was reduced to Kalman filter formulation

  C.M. Roitmayr, thesis, (Stanford U.,1986; supervisor Breakwell) title: "Orbital Mechanics and Position Estimation for an Occultor Spacecraft"

Engineering requirement: have edge advance slowly enough to bring out angular structure at a statistically significant level, and one must be sure diffraction does not become appreciable

"Slowly enough" is relative **– depends on the detection system**, and the astronautics

High Orbits and Occultations

Wood & Breakwell (1987) Artificial Occultor Concept

Delta-wing occultor, in orbit plane perpendicular to lunar orbit

Considered, rejected, LEO for specific impulse → Lunar altitude

Steerable to targets by combination of Sun's gravity and thrusters

***Navigate using GPS from farther side of Earth* – the right idea**

Navigation concept reduced to Kalman filter; fueling, commanding scoped

(but programmatic target dates proved "optimistic"…)

Main idea:

Steerable, smooth edge,

To access *entire* sky for high angular resolution on targets

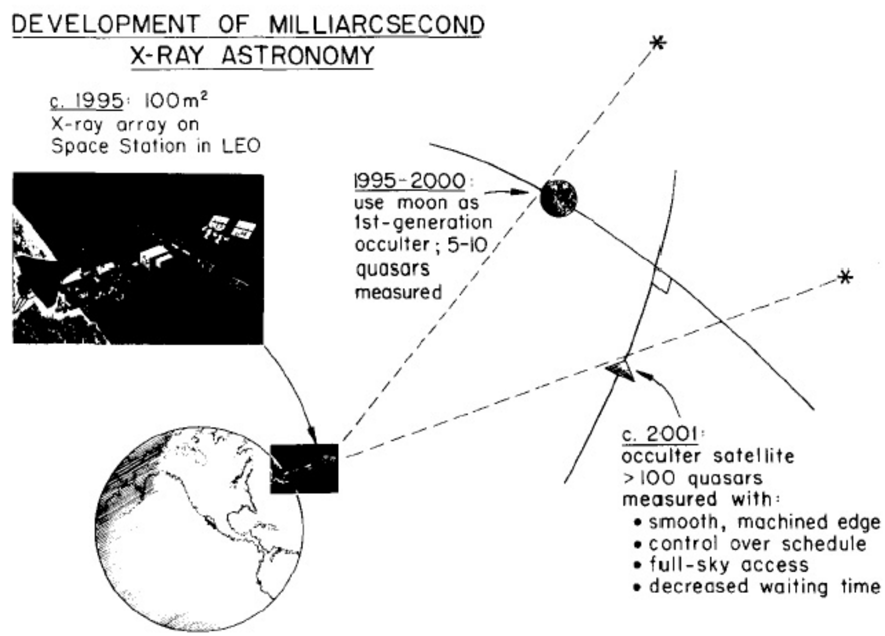


Fig. 2. Development of milliarc second X-Ray astronomy, based on use of the NASA Space Station as the site for a large array.

Also,

an example of long straight lines in space using X-rays and occultations.

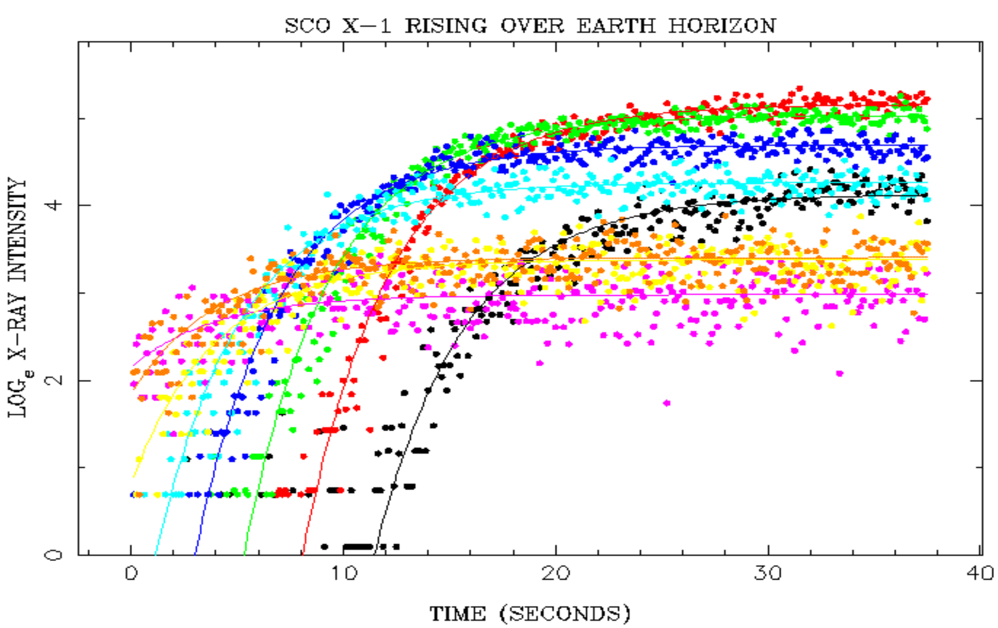
Late 1980s

Occultations and Eclipses: LEO transit applications

Earth occultations are a special case of eclipses, *i.e.*, by atmosphere when source transitions at earth limb.

Atmospheric occultations are gradual, not sharp

Earth occultations can provide position information, referenced to the Earth, but it is necessary to model the atmosphere (as well as oblateness) to fit occultation curves.



Ginga (1987-1991) generally **scheduled to avoid** observing earth occultations, but occasionally observed them unintentionally

A (rising) transit of Sco X-1 (1989) provided inspiration during development of USA Experiment

This horizon transit would not have been observed had Ginga been in orbit used for scheduling. The orbit had changed.

Thus the transit in effect measured change of the orbital elements, i.e., was navigational information

Occultations and Eclipses, cont'd: atmosphere issue

importance has grown with concern over climate change

It can work another way, too:
Occultations can provide atmospheric diagnostics for remote sensing

A study of Earth-occultations of the Crab Nebula using USA and RXTE was used to derive atmospheric density profiles (Determan et al, JGR, 112, AO6323 (2007))

When X-ray Earth occultations are used to probe the atmosphere they are most sensitive in the altitude range from 80 to 150 km. This is the range where models predict effects associated with global climate change

A06323 DETERMAN ET AL.: MEASURING ATMOSPHERIC DENSITY A06323

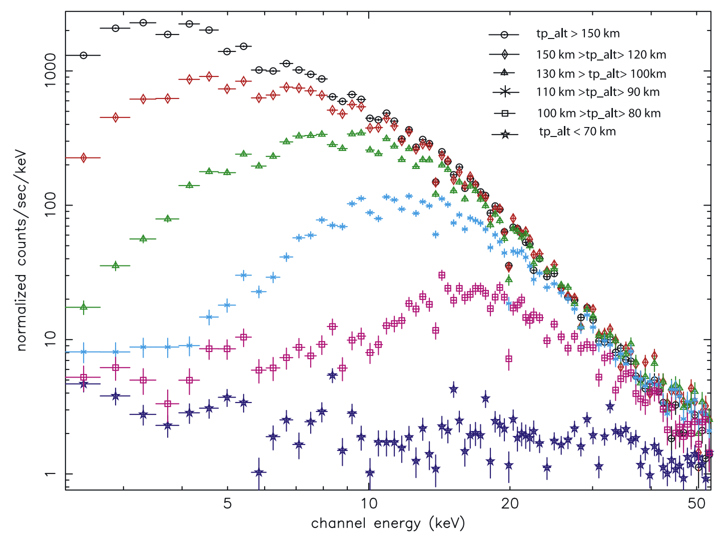


Figure 4. PCA measurement of the Crab spectrum through the attenuation process. Spectra 1 and 6 are, respectively, unattenuated and fully attenuated. The altitudes indicated are approximate. Note that, in the first 10 s (3: 130 km > tp alt > 100) of the occultation, the lower energy photons below 5 keV are dramatically reduced. As the occultation progresses, we see selective absorption as the atmospheric density increases with the decreasing tangent altitude.

Roble, R.,"*Major Greenhouse Cooling (yes cooling): The upper atmosphere* response to increased CO2," Rev Geophys Suppl., pp 539-546 (1995)

Mid-to-late 1980s:

USA Mission

- USA mission concept: **large exposure (area x time product**) on sources, using long observing times
- ***Much of the rationale for USA was systematic study of X-ray sources for celestial navigation.***
- USA was **essentially an avionics package,** based on X-ray sensors viewing celestial sources.
- ***Instrument Desription:*** Ray *et al.* in *X-ray Astronomy,* Bologna, Italy, 1999,(White, Malaguti, and Palumbo, *Eds.*)

Proposal 1988; developed 1988-99; USA flight was 1999-2000

Position, time-determination, and attitude were all deemed worthy goals, as was time transfer

This is a broad interpretation of X-ray navigation

The "cold start" problem was particularly interesting (still is)

It requires using bright sources

One does not start cold on faint, 100-micro-Crab sources

USA: Advocacy and Development Phases

Two papers (SPIE) published in the design phase of the USA program surveyed the concepts of X-ray navigation,

Navigation Studies Utilizing the NRL-801 Experiment and the ARGOS Satellite

- K. S. Wood in *Small Satellite Technology and Applications III*, ed. B. J. Horais, SPIE Proceedings vol. 1940, 105 (1993).
- Wood et al, SPIE Proc 220, 19 (1994)

Position: pulsars and occultations/eclipses

Attitude: measuring residuals on transits

Timekeeping: pulsar phase determinations; time transfer using rapid variability in periodic or aperiodic sources

Thus, USA supported feasibility exercises on *several* navigation ideas

ARGOS satellite had various truth sources for comparison

In fact, feasibility demonstrations rather than full system prototyping is where X-ray navigation remains today, including SEXTANT

USA supported development of X-ray navigation other ways as well. The first Ph.D theses on X-ray navigation (Hanson (1996); Sheikh (2005)) were done in conjunction with the NRL program

USA's Role in Autonomy

Computation in support of navigation was recognized as essential for X-ray navigation of satellites

Being able to compute without errors in the space environment is also **essential to *any* autonomy**.

The USA Experiment therefore incorporated a testbed

(Advanced Space Computing and Autonomy Testbed – ASCAT)

for computing, believed the first of its kind. It compared performance of two strategies for reliable computing in space, namely radiation-hardening of processors vs. fault-tolerance software.

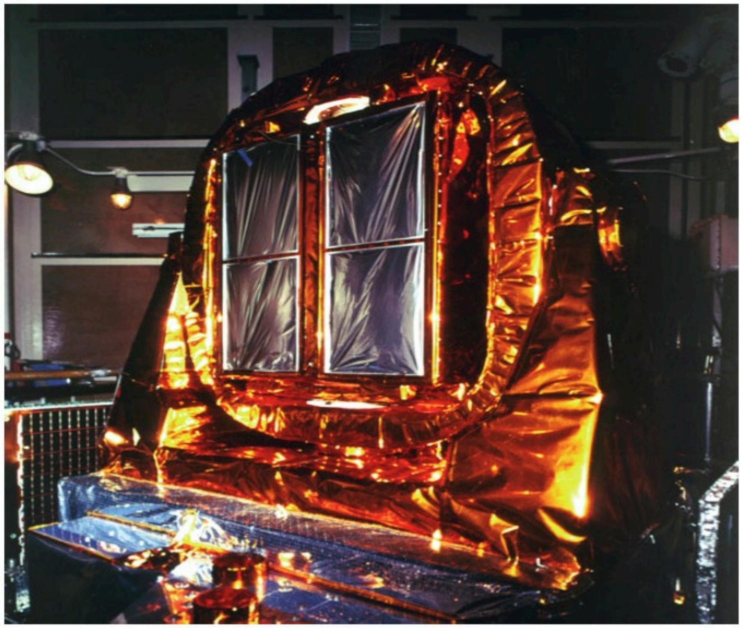
For discussions of ASCAT testbed results see:

Lovellette, KSW, et al, IEEE Aerospace Conf Proc., Big Sky, MT [ISBN 0-7803-7232-8] (2002)

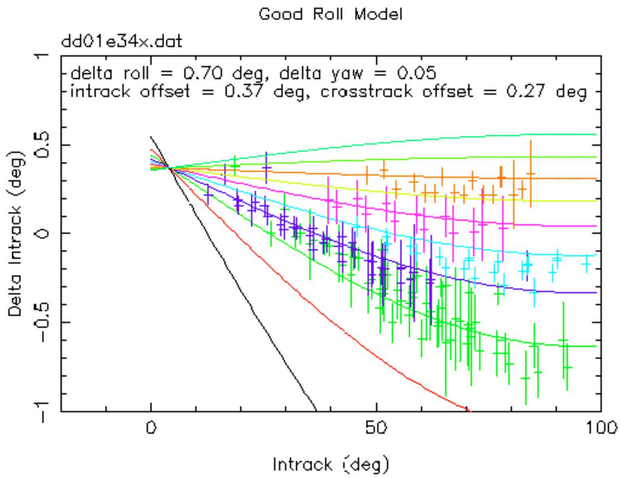
Lovellette , KSW, et al, IEEE Aerospace Conf Proc., Big Sky, MT [ISBN 0-7803-7652-8] (2003)

– Computer testbed was able to receive the X-ray event data stream onboard
– **The rad-hardening *vs.* software trade explored with USA/ASCAT remains a research topic, applicable to autonomy**

USA, cont'd



- Design and execution
  - Large proportional counter
  - Mounted in 2-axis gimbal
  - Could track X-ray sources independently of spacecraft
- USA was used as an X-ray star-tracker to diagnose and correct a problem that developed with the *ARGOS* spacecraft attitude control.
- **This may be first use of an X-ray sensor as input to attitude control of a flying satellite.** See Wood et al "The Unconventional Stellar Aspect (USA) Experiment on ARGOS," AIAA Space 2001 Conference and Exposition, paper AIAA 2001-4664 (2001)" **(Feedback loop was via ground)**



USA, cont'd

Millisecond pulsars (MSPs) were found (using ROSAT) to be X-ray sources while USA was in preparation

- implications for X-ray navigation were recognized
- bright MSPs (B1821-24) were added to USA observing plan

MSPs were too faint to be easily detected by USA

Later XNAV program explored technology approaches to seeing these faint sources, including large arrays of silicon pixel detectors and large arrays with collector optics in front

But for USA the Crab Pulsar was the principal target for timing applications studies. **Also looked at AXP, 4U 0142+61**

Wood et al., AIAA 2001-4664 (2001)

Ray et al. Bull. AAS, Vol. 34, p.1298 (2002)

Ray et al. Bull. AAS, Vol. 35, p.641 (2003)

USA to XNAV (early 2000s)

… and thence to *Fermi* LAT and SEXTANT

- **USA led to patent for pulsar-based X-ray navigation** **(U.S. Patent No 7,197,381; *Navigation System and Method Utilizing Sources of Pulsed Celestial Radiation*; filed 2003; awarded 2007)**
  - **Patent *scope* was constrained by our own prior publications from 1990s.**
    - **U MD Ph.D. student Suneel Sheikh collaborated on USA and on patent, while completing his thesis on pulsar-based X-ray navigation (2005), the first X-ray navigation thesis to include MSP-based strategies;**
    - **Also, Sheikh, Pines, Wood, Ray, Lovellette, Wolff; JGCD,29, No.1 (2006)**

- **Concurrently DARPA ran a program called XNAV** to explore practical approaches to **pulsar-based X-ray navigation**. These ideas were associated with the possibility of a demonstration with a payload attached to the international space station.
- Two design approaches were evaluated using a pulsar simulator
- NRL, LANL, Ball Aerospace, and NASA GSFC participated
- **Further improvements along these lines later led to NICER/SEXTANT**

- **During these same years the NRL group was simultaneously working on the *Fermi* Large Area Telescope (LAT)**
  - **Following launch (2008) the Fermi LAT would make many discoveries of new gamma-ray pulsars, including MSPs. (See talk by P. Ray)**

Early 2000s Historical aside:

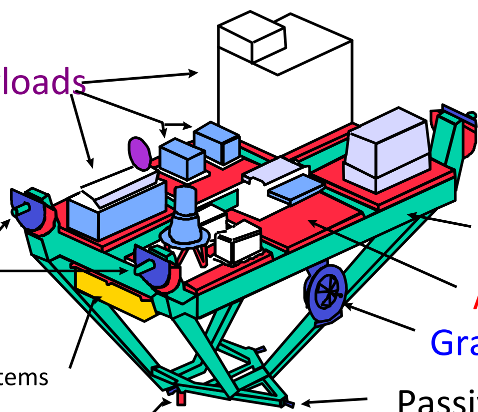
A USA follow-on … never flew, but had *heritage*

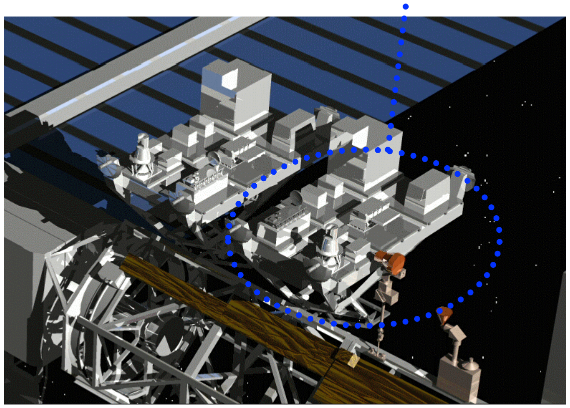
NRL-306 (SIXI) (Proposed 1993)

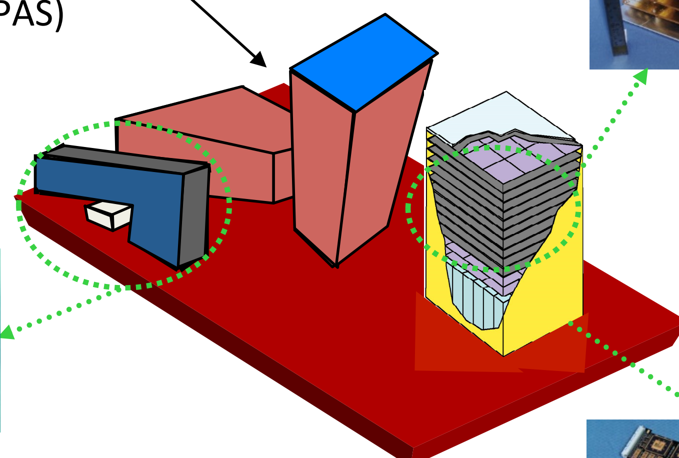
SIXI was designed to continue X-ray navigation after USA.
The idea of SIXI fed into the formulation of the DARPA XNAV program

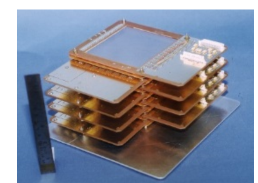
- SIXI is well-matched to the Express Pallet on the International Space Station

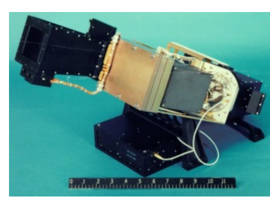
K.S. Wood, *"The Silicon X-ray Imager (SIXI) on ISS Express Pallet"*
AIAA-2004-0433 (2004) This had an overview of X-ray navigation to that point.
See also: Ray P. S., Wood K. S., Phlips B. F. "Spacecraft Navigation Using X-ray Pulsars", NRL Review 2006 ; http://www.nrl.navy.mil/content_images/06FA5.pdf

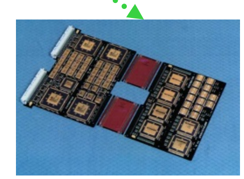












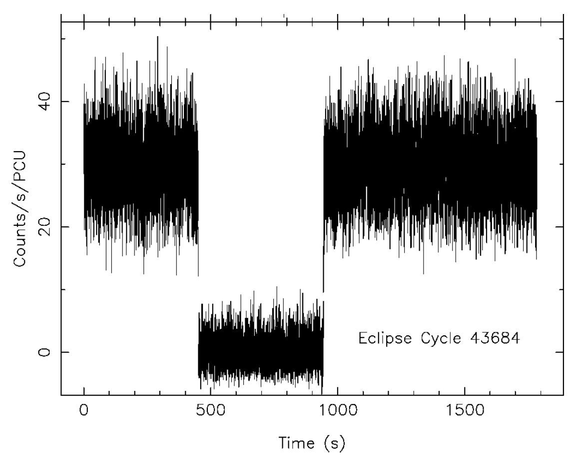
RXTE Era (1990s to 2011)

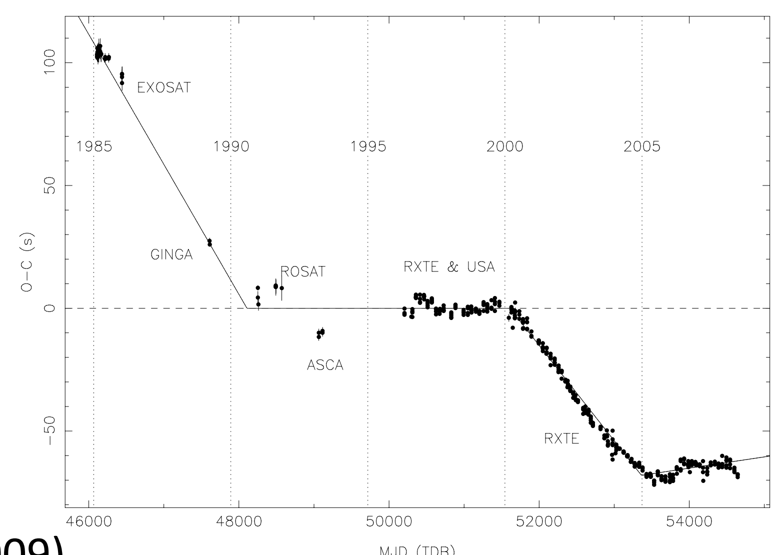
Used RXTE to continue work on both Themes during RXTE life

- **B1821-24 (MSP) observed for ~ 200 ks; ToA compared with ephemeris**

  Ray *et al.,* in "40 Years of Pulsars," AIP Conf. Proc. 983, 157 (2008)

- **Exo 0748-676:** eclipses are high signal to noise, but disappoint as clocks
  - Eclipses were seen from time of Exosat through RXTE;
  - Source later went into quiescence (October 2008)
  - **Eclipses are (usually) sharp, high signal, easily timed**
  - **Source showed unexpected level of timing residuals, using RXTE + USA**
  - **Still not well understood (see figure below, right) … work for the future**



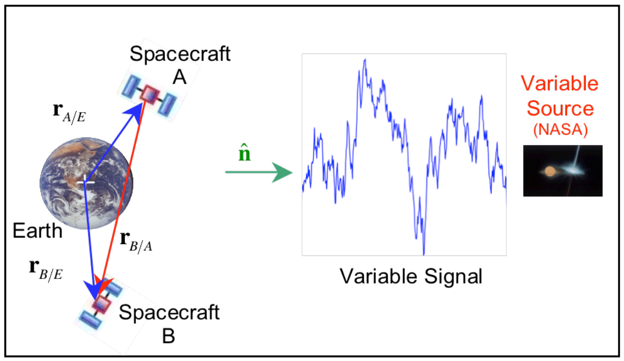


Wolff et al., Ap. J 668, L151

Wolff, Ray, Wood, and Hertz, Ap.J. Suppl. 103,156 (2009)

RXTE Era (1990s to 2011)

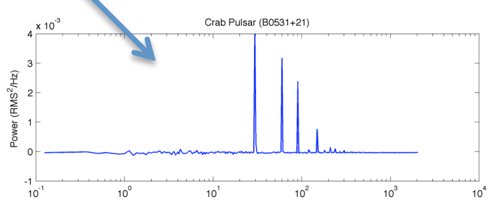
- Navigation study using Crab, Cyg X-1, and GRS 1915+105
- Use short timescales of intrinsic variability in the source
- Periodicity not required, but may give best results
- Can be used for relative navigation or for time transfer
- Limitations come from longer timescales (red noise) and Poisson noise, but can reach tens of microseconds

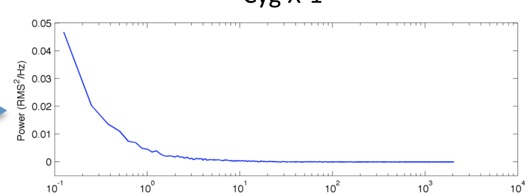


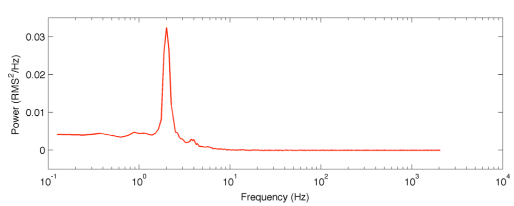
Sheikh, Ray, Weiner, Wolff, Wood
ION 63 (2007)

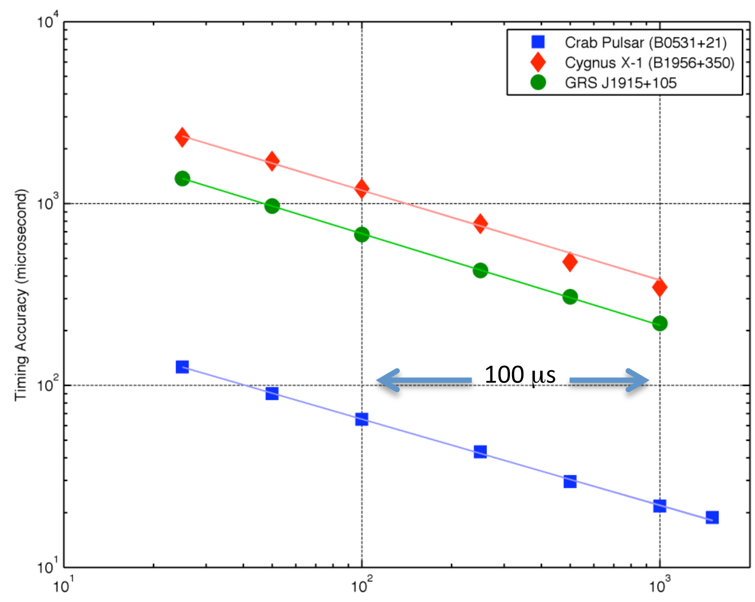
Two Black Holes

Crab Pulsar (NS)









Lunar Occultations of the Crab using RXTE (2011)

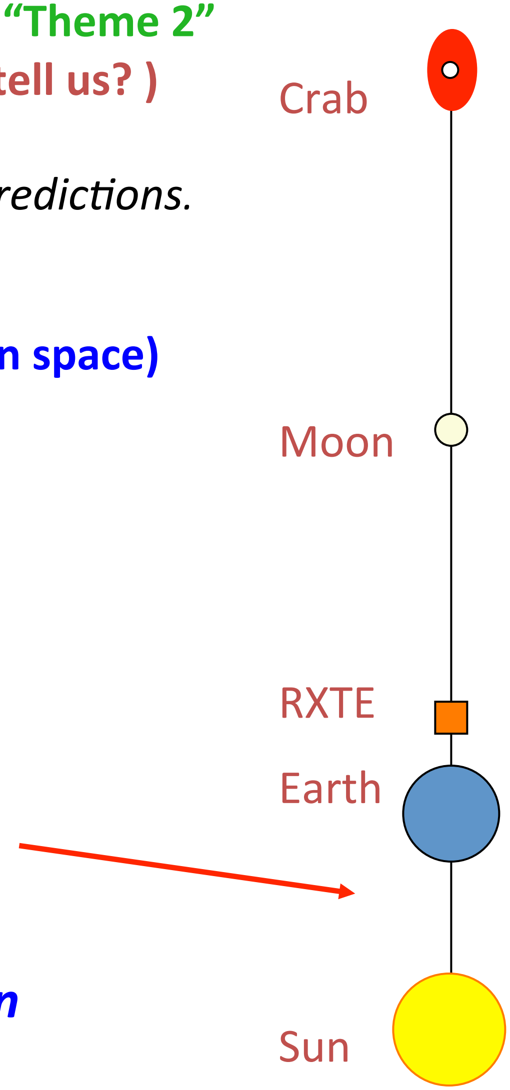
Planning involved celestial mechanics, RXTE Orbit

- Lunar orbit precesses with period ~18.6 years.
    - **Occultations of Crab at ~9 year intervals**

End of RXTE was imminent; this would be last RXTE exercise on "Theme 2"

- **Needed several tries for success –(by the way, what does that tell us?)**
- **RXTE mission life was extended** for these observations
  Precise calculations for planning required predicted RXTE orbit predictions.

(note once more: long straight lines in space)



Success!

13 Nov 2011: one lunar ingress + one egress

+ one occultation by Earth atmosphere

11 Dec 2011: one lunar ingress

There was also a lunar eclipse within hours of that time –

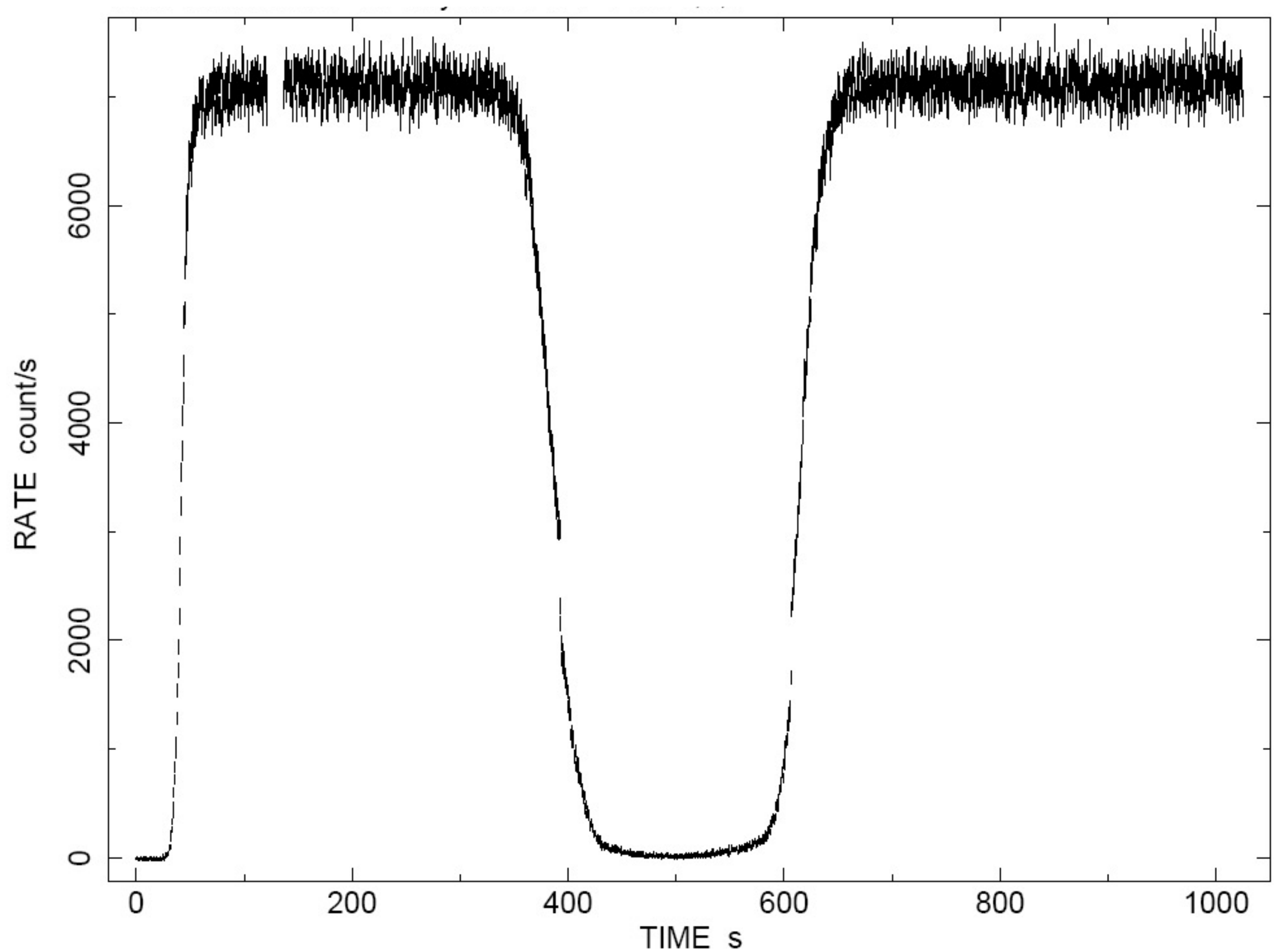
Sun-Earth-RXTE-Moon-Crab were roughly co-linear

Total yield = three occultation curves

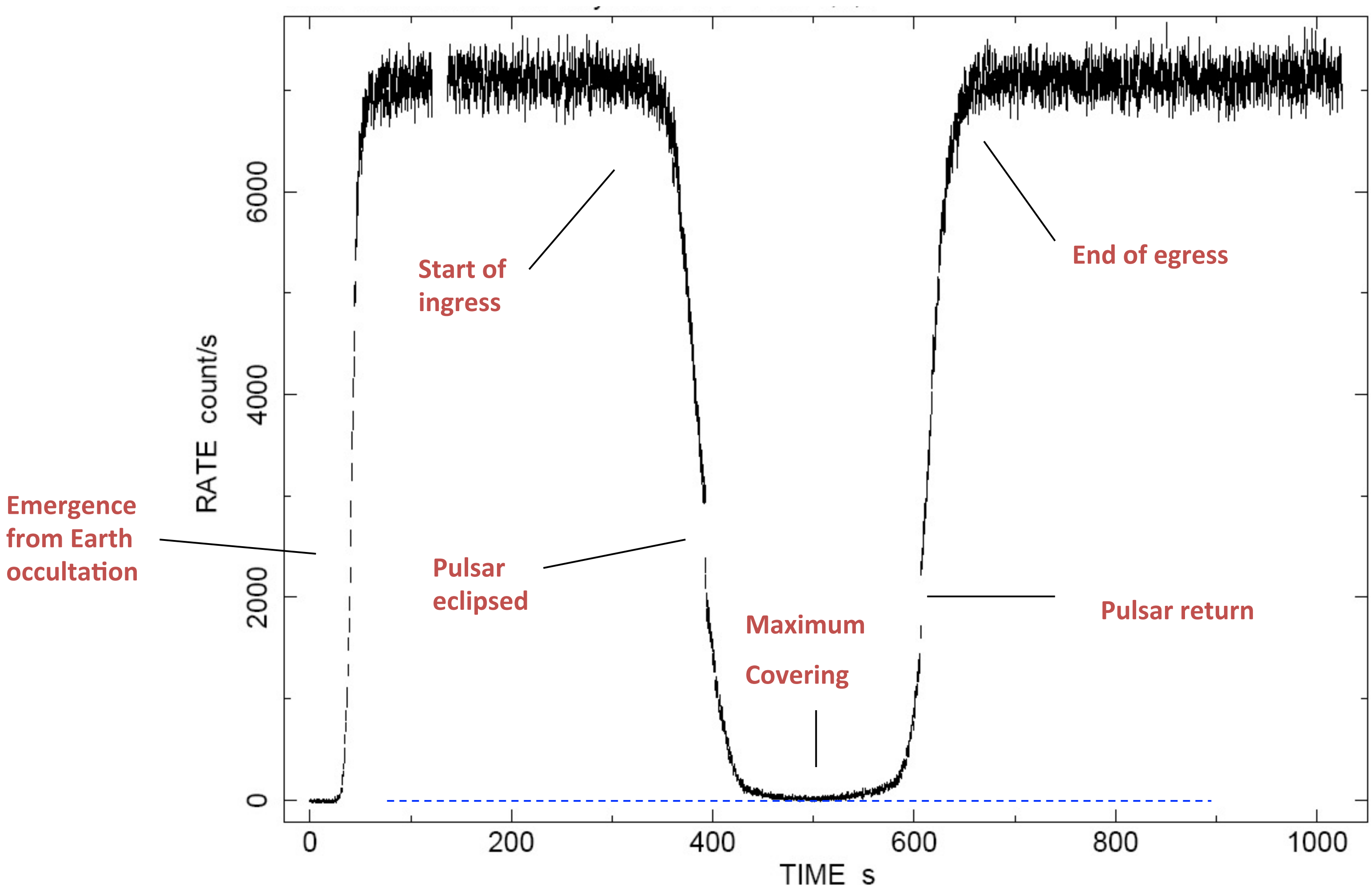
This should remain the best set of X-ray Lunar occultation profiles of any celestial source for years to come

Full Observation Including Initial *Atmospheric* Egress

Nov 13, 2011 Lunar occultation of Crab Observed by RXTE PCA



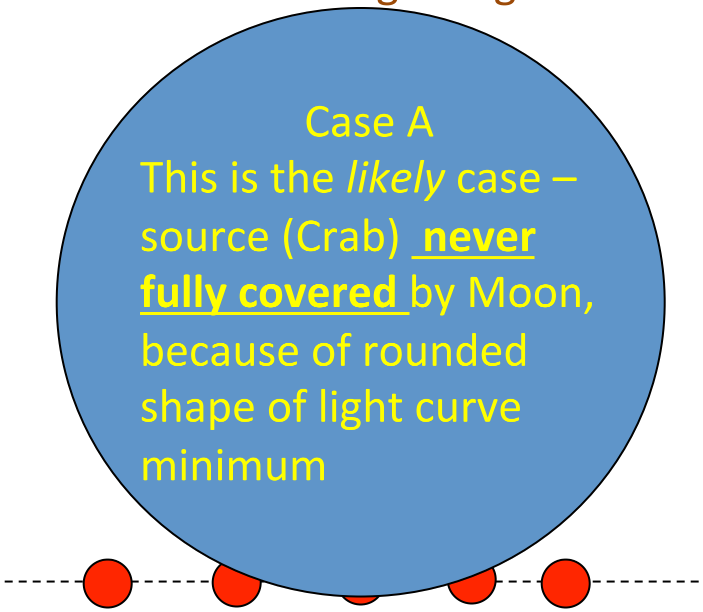
Nov 13, 2011 Lunar occultation of Crab Observed by RXTE PCA

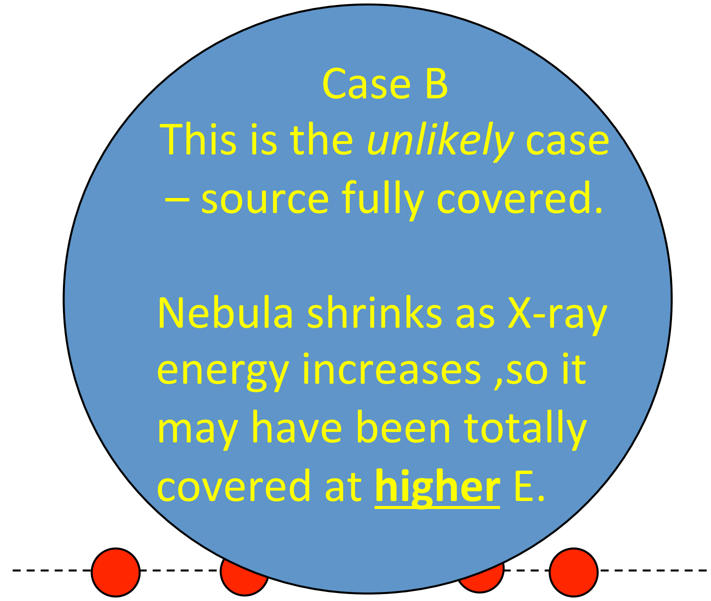


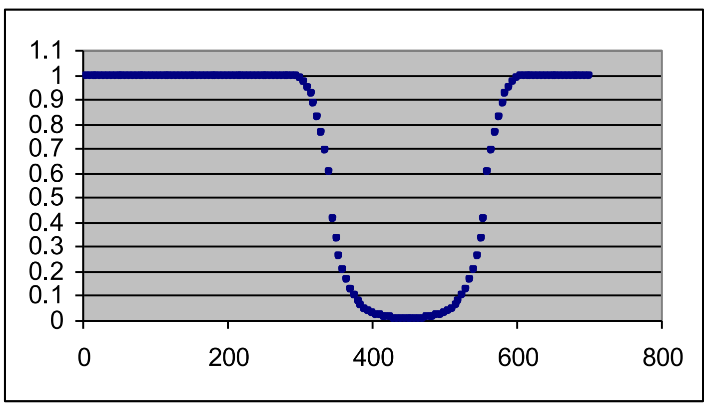
from Wood et al, 2012
Workshop on *16 Years of Discovery with RXT*E

Idealized models (*circular symmetry, uniform velocity*)

for Nov 13 grazing occultations, were they Case A or Case B?

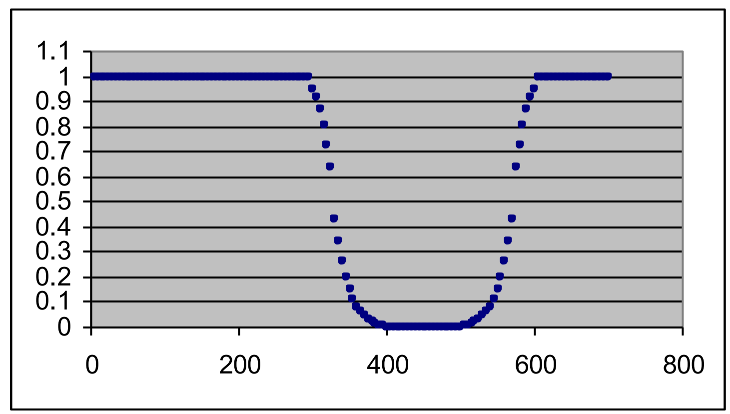






Centrally enhanced brightness

Incomplete eclipse



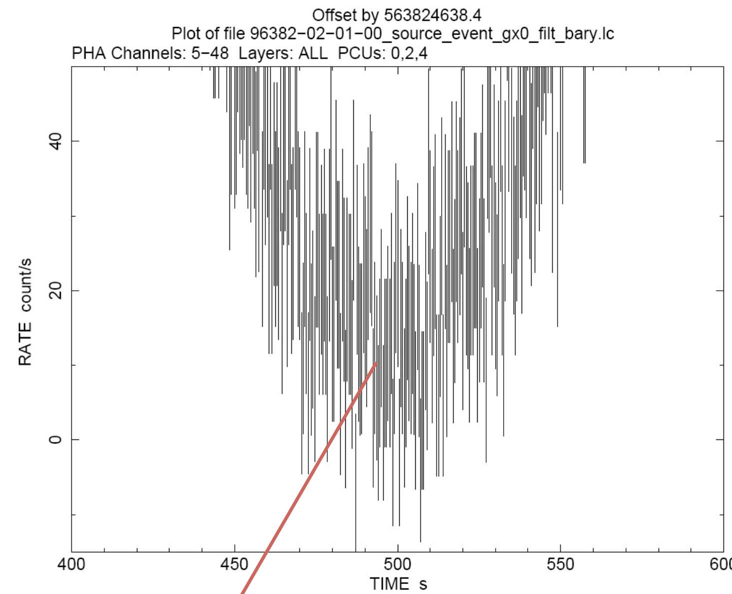
Centrally enhanced brightness

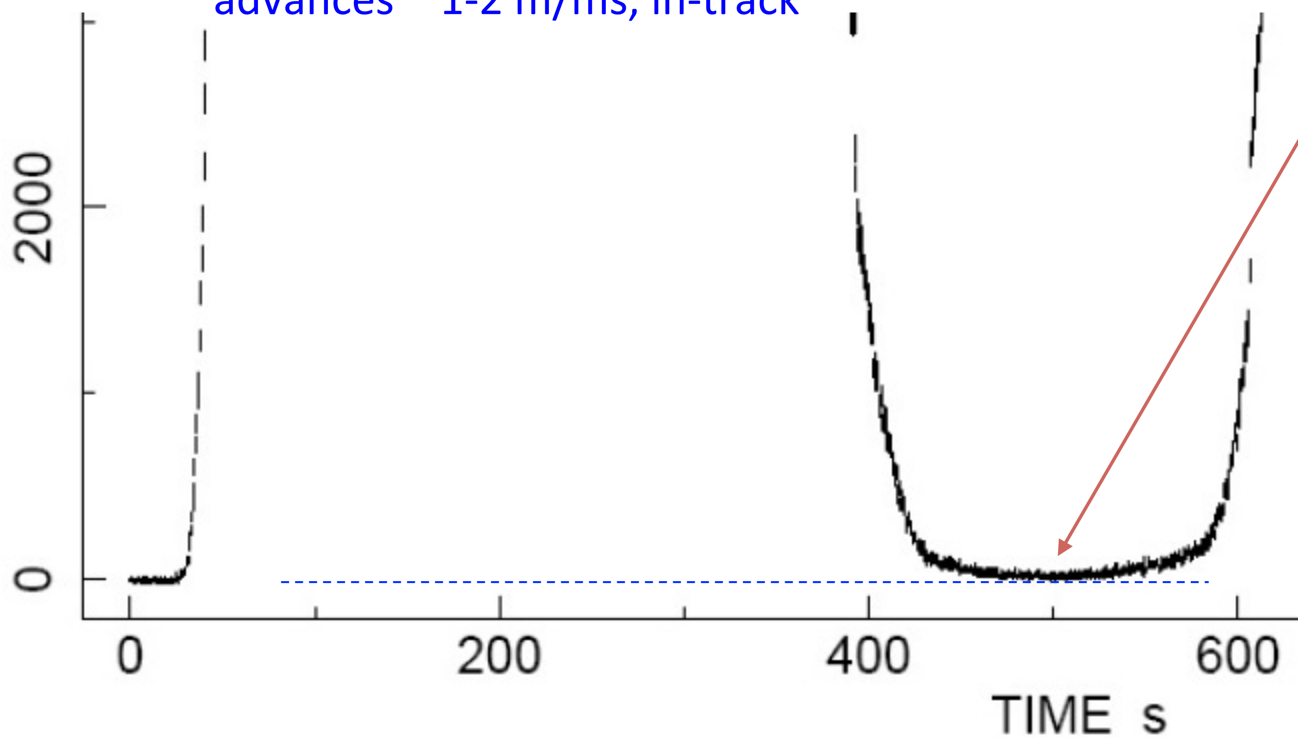
Complete eclipse

Expansion of Light Curve, Near Maximum Covering

(Nov 13, 2011)

Note: 1 km of cross-track perturbation (or error) in RXTE position equates to ~ ½” on limb position relative to Nebula, or ~1% of Nebular overall extent. Lunar shadow advances ~ 1-2 m/ms, in-track

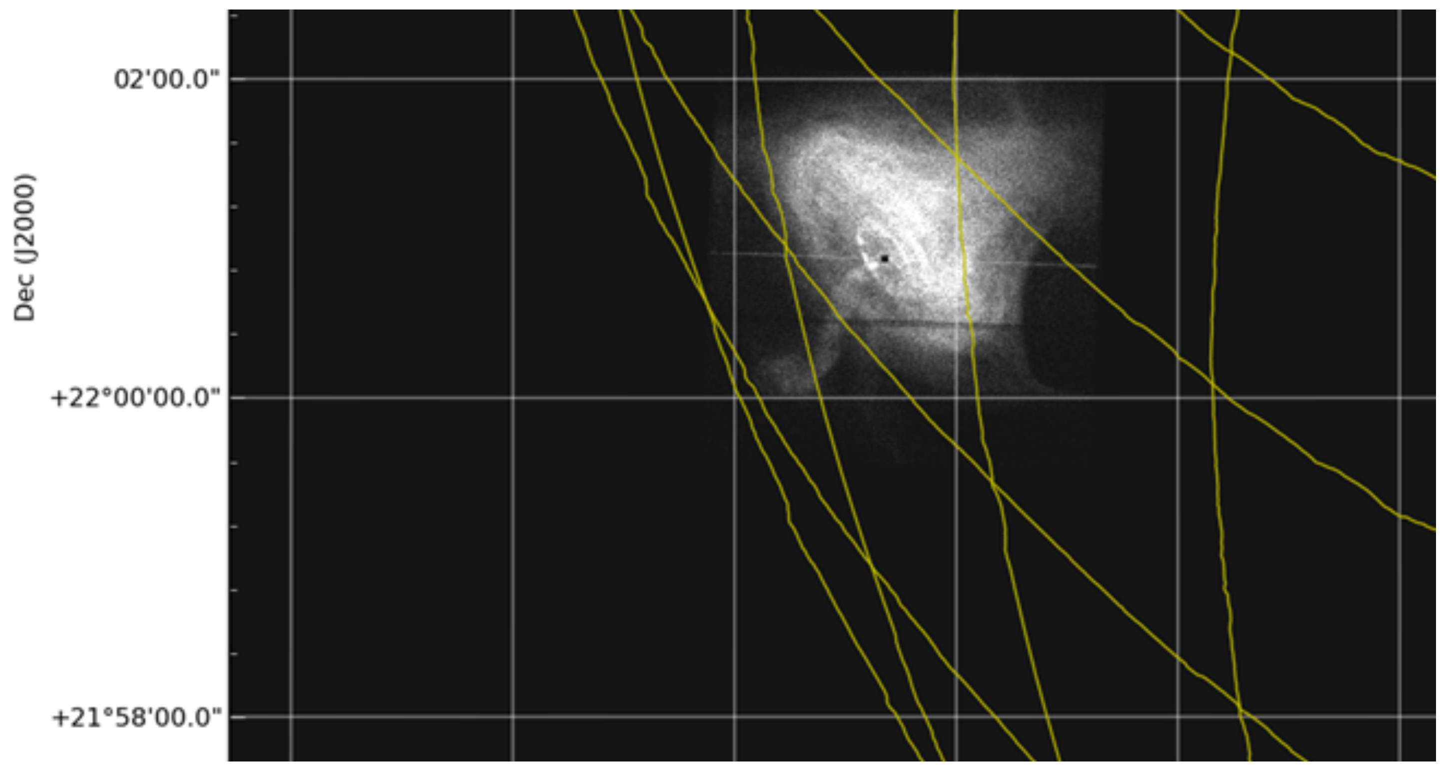




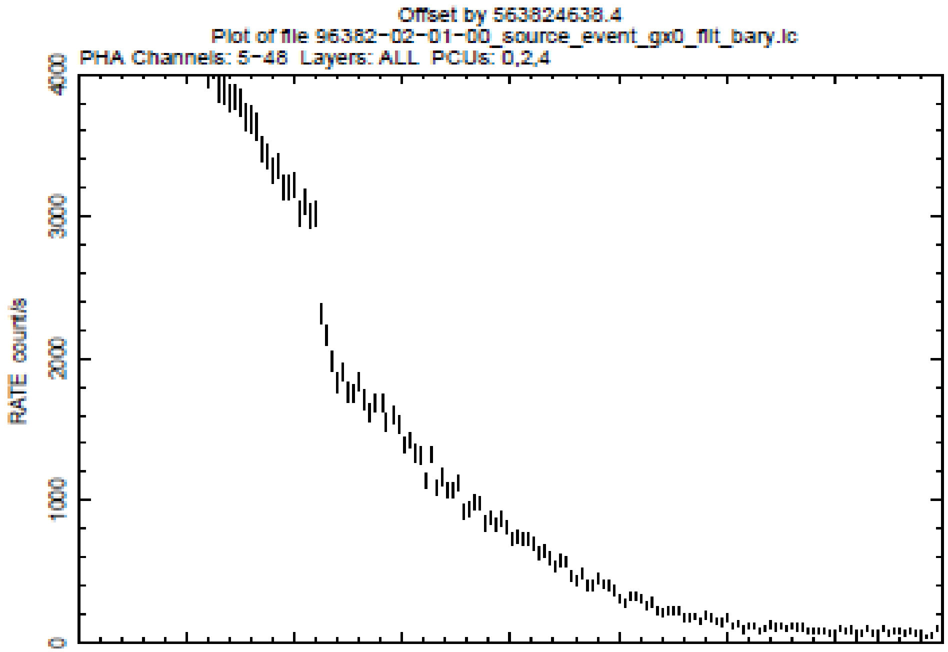
U-shape of bottom argues for Case A over Case B, at least for total count

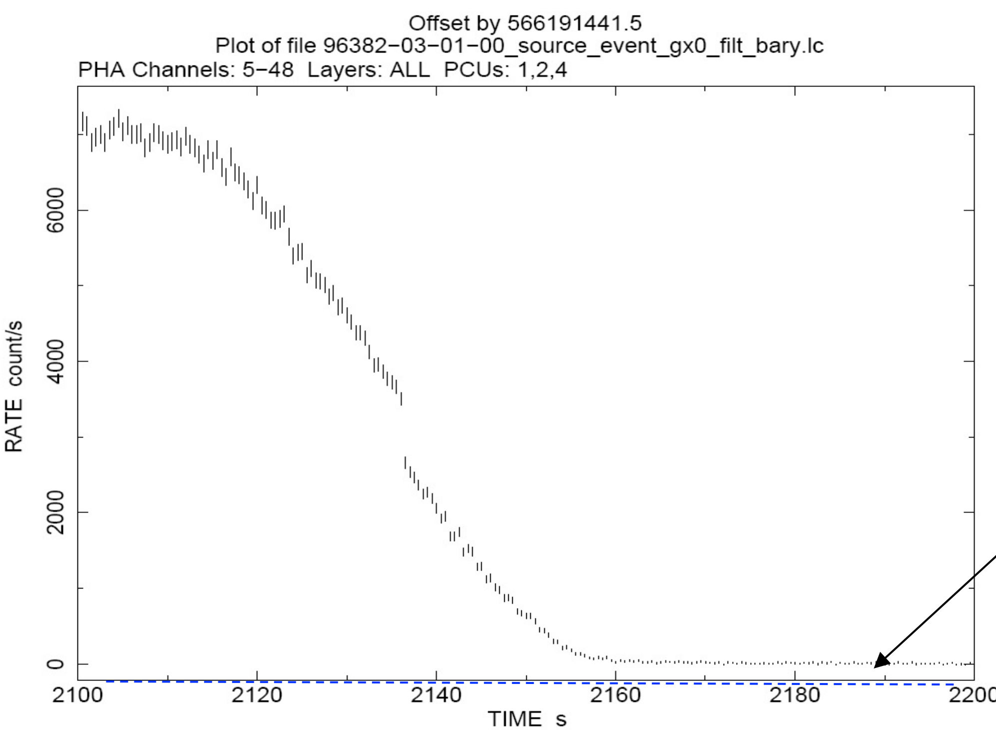
Lunar Limb and Nebula

- lunar limb positions, calculated using terrain and best estimate of RXTE orbit, superposed on X-ray image for times near maximum coverage.
- **If inverted for navigational content (perturbing orbit but freezing assumed shape), light curve would yield cross-track as well as in-track information**



Looking Near Pulsar Ingress





13 Nov 2011

Ingress side

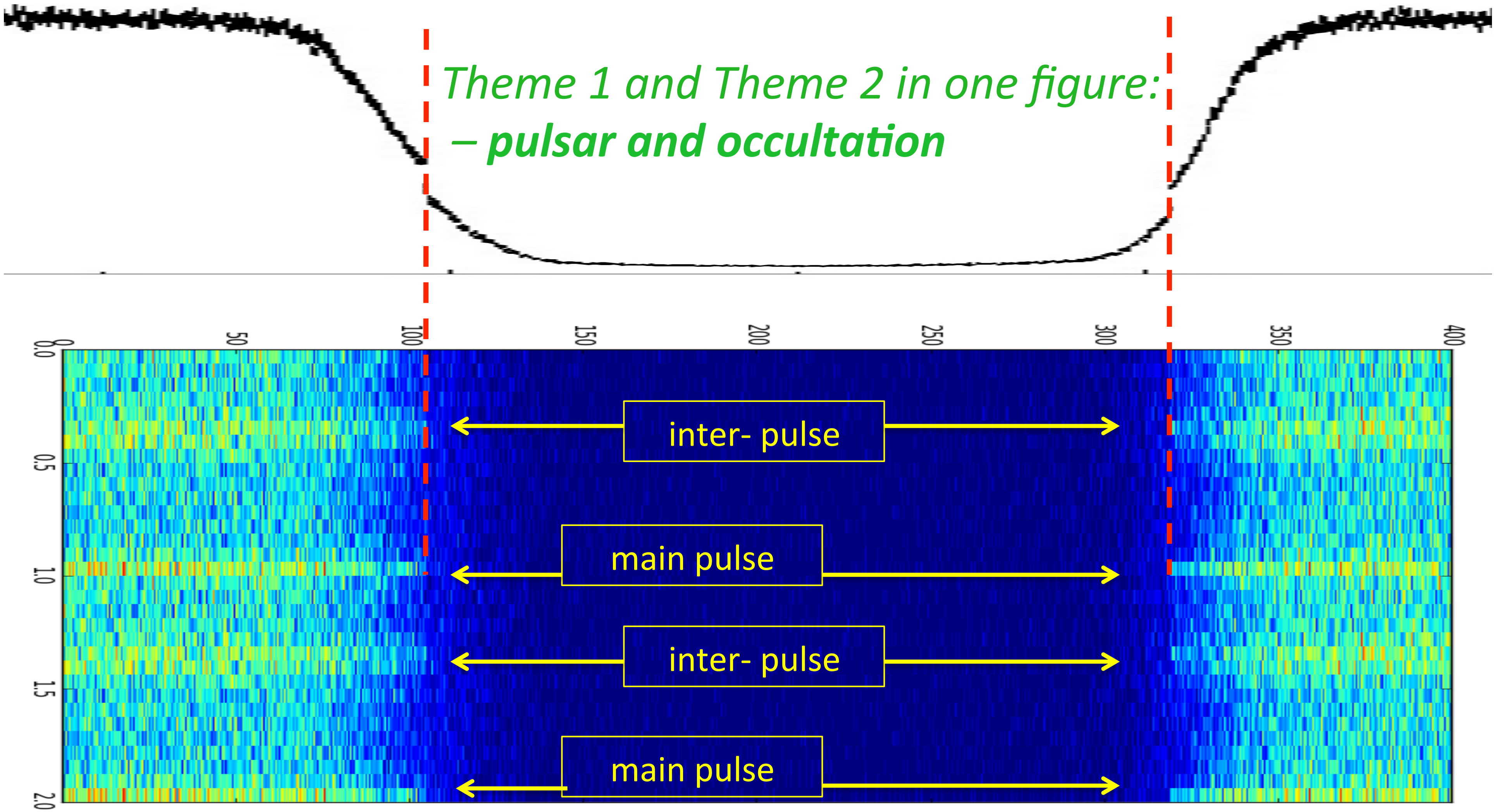
Recall (e.g., from earlier 1964 occultation slide), that derivative of light curve gives brightness distribution in strips parallel to limb. Slope differences relate to brightness gradients

11 Dec 2011

This time, not grazing impact, *i.e.*, this one is absolutely "Case B"

Watch the pulsar blink out and return!

Overall elapsed time increases to the right; in vertical direction one sees the pulsar (2 cycles)



Ideas and challenges

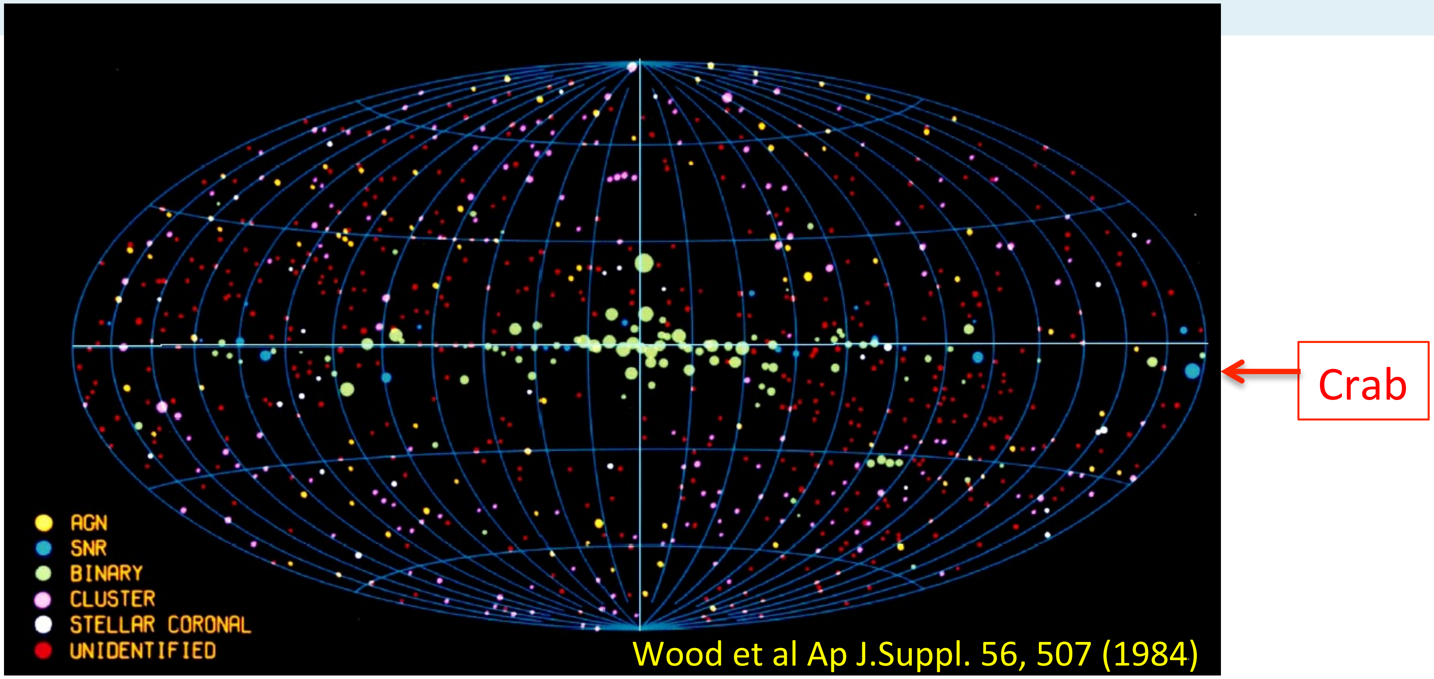
NRL Program Continues: What's Next?

- **Pulsar X-ray navigation is being explored actively right now**
  - Simulations and algorithm development for SEXTANT (to fly in 2016)
- **NICER/SEXTANT should also explore some of the other timing applications that have been discussed**
  - MSP ToAs/residuals, with better orbit determination and ephemerides than in USA, RXTE
  - Will observe black hole candidates under GI program; continue relative navigation
  - May observe eclipses or occultations, depending on availability
  - If mission lasts several years, may see another Crab occultation
- **Continuation of *Fermi* will provide new gamma-ray pulsars**
  - Fermi mission will seek approval for continuation past 2018
  - It will operate concurrently with NICER/SEXTANT
  - X-ray study of issues such as X-ray / gamma-ray phasing will be facilitated
    - PSR J1813-1246 NuSTAR Cycle 1 observation

- Very long range: X-ray interferometry missions (such as MAXIM concept) will need to have very fine attitude knowledge/control. X-ray sensors may be part of the solution to that.
- More generally, X-ray methods provide many useful features, for example, the ability to determine long straight lines in space
- Active concepts such as X-ray communication are also possible

Cautionary Consideration

- **HEAO catalog below shows sources down to ~ 1 milliCrab**
  - **Top ~800 sources have dynamic range of ~10,000 in flux**
  - **Color coded classes have various different uses**
- **MSPs are ~ 30 x fainter than faintest sources depicted here!!**
  - **May have brighter sources nearby at small angular separation**
- **Crab is bright, but also young and noisy; Pulsar is ~10% of Nebula;** **2nd brightest RPP is much fainter. (SEXTANT continues to utilize Crab Pulsar for its navigation demonstration, is not purely MSP-based.)**
- **Navigational systems need to exploit brighter sources and high modulation effects in cold start or autonomous initialization**



Summary

- **The program in X-ray Navigation and related topics at NRL spans more than five decades**
  - Early rockets: pulsars, occultations, variability
  - USA program (1980s – 2000); first space experiment in X-ray navigation
  - First Ph. D theses in X-ray navigation (Hanson, Sheikh)
  - XNAV program at DARPA; now NICER/SEXTANT
- **The program has explored variety of techniques**
  - Pulsars were always part of it
  - Attitude, position, timekeeping, time transfer
  - Detection technologies
  - Occultations and eclipses
- **Going forward, there remains a role for other X-ray methods to complement pulsar navigation**
  - **If "XNAV" means pulsar navigation, then it is a *subset* of X-ray Navigation**
  - In particular **there can be a continued continued role for occultations** and eclipses, especially for operations near planets
  - The complementary approaches can utilize the *brightest X-ray sources*
  - It is not difficult to combine these methods