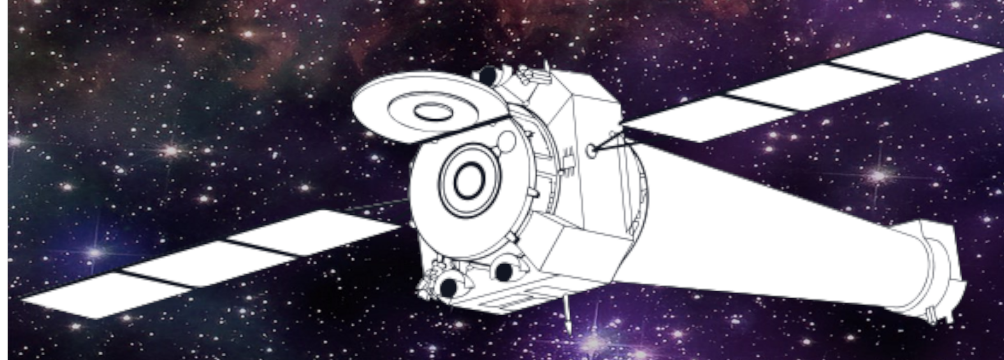

25 YEARS OF CHANDRA ORBIT EVOLUTION

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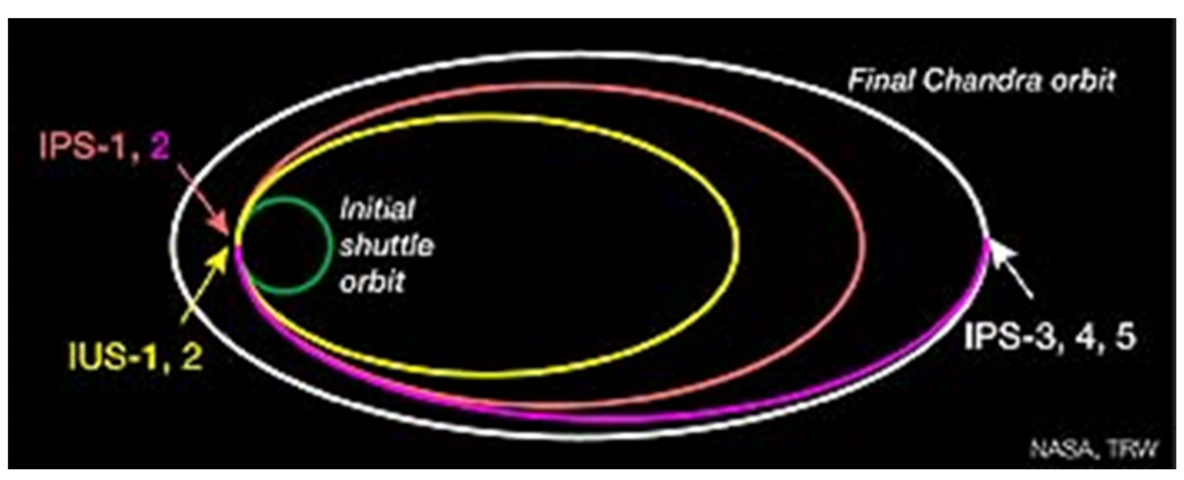
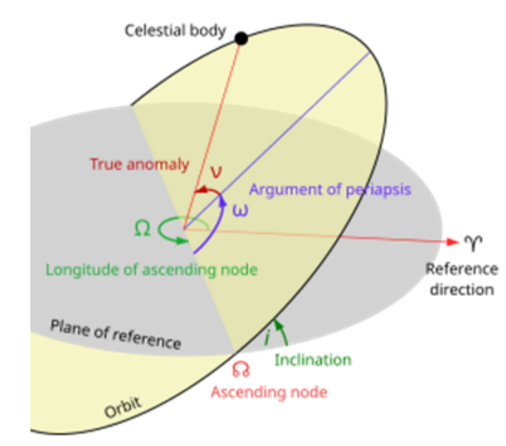
Initial Orbit Design

In 1999, the Observatory was launched aboard STS-93 from Kennedy Space Center into a circular, low-Earth parking orbit, then deployed after activation and checkout. Two upper-stage (IUS) burns put Chandra into a highly elliptical orbit, followed by two burns from its own Integral Propulsion Subsystem (IPS) thrusters to eventually raise the apogee to its operational level of 140,000 km. Finally, three more burns at this apogee raised the perigee to the level of 10,000 km, placing Chandra in its operational configuration.



The parameters for the operational orbit were optimized by satisfying the conditions as defined: (1) Minimize the maximum eclipse duration to less than 2 hours over the 5-year mission life to preserve battery and science observation time, (2) maintain perigee altitude above 9,000 km because of potential adverse radiation environment, and (3) provide maximum DSN visibility during the mission.

The orbit designers knew that high apogee, highly elliptical orbits experience dramatic changes in the shape and orientation due to the strong influence of the Moon and Sun at apogee. Pre-launch analysis showed that the orbit became more circular over the first few years of the mission, as the perigee rose higher and the apogee fell lower. Then the trend showed to reverse itself, become more eccentric over another few years. Right ascension (or longitude) of the ascending node (RAAN), argument of perigee, and the inclination were shown to change significantly over this period as well, all orbital parameters that describe the rotation and "pitch" of the orbit with respect to the Earth.

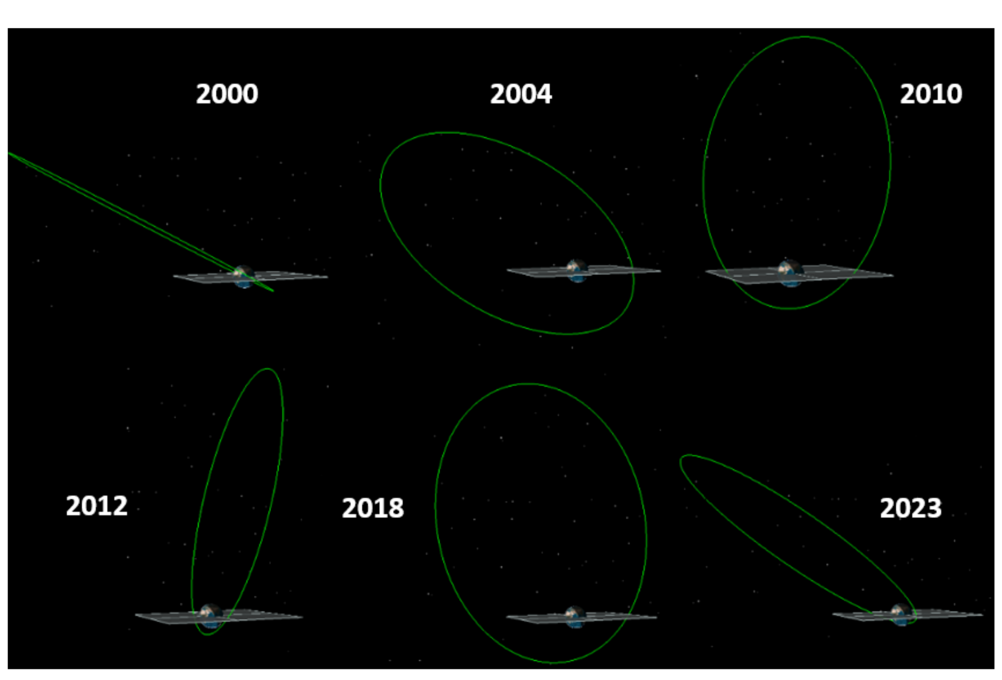


These parameters primarily affect eclipse conditions and available science time, as the spacecraft moves into regimes that place it further into Earth's shadow and/or magnetosphere for longer durations. A critical altitude was also baselined at the time to 60,000 km, below which it was said that science data may be taken but could be subject to large environmentally-induced noise.

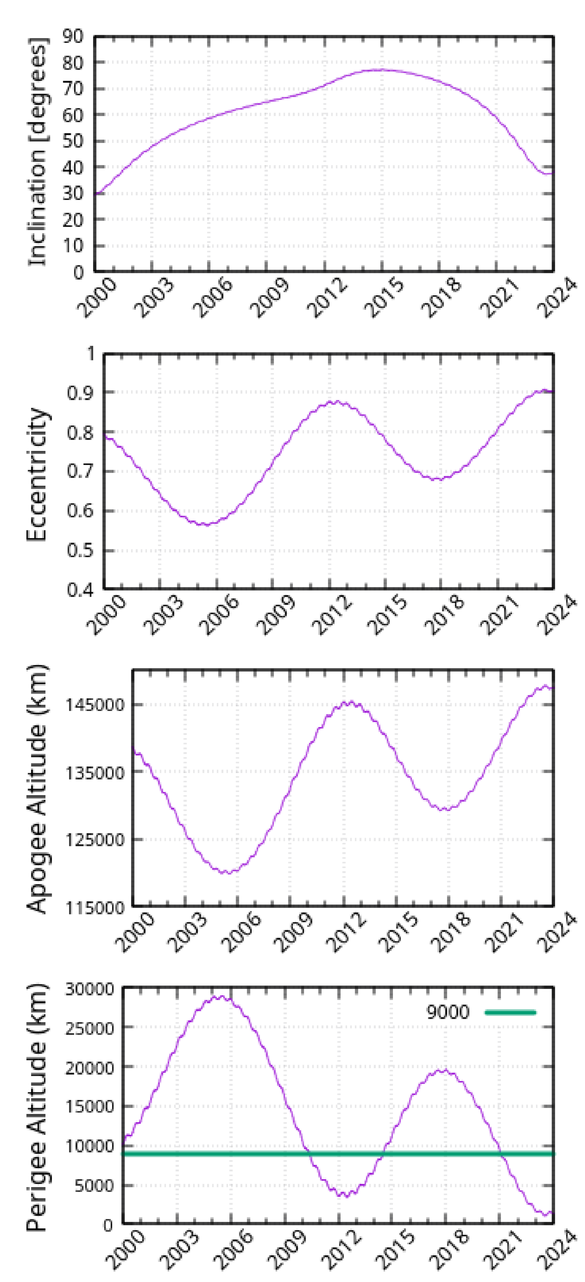
This early study only looked out 10 years, but with the mission life requirement being just 5 years, this was sufficient in showing the nature of the orbit for the future. It was accurate for the time period it covered, but further analysis would be needed to understand some of the more "extreme" orbital regimes that were to come in Chandra's future.

Ever-Changing Orbit and its Effects

By design, Chandra has no station keeping capability. Therefore, as perturbations cause its orbit to drift, operations must adapt to changing orbit parameters. With the mission having continued beyond not just the original 10-year predictions, but now past 25 years at the time of writing, it has been necessary to extend the original orbit predicts and perform additional analyses on potential mission impacts at several points throughout the mission. The figure below shows how the shape of the orbit has changed at several stages of the mission, namely the years 2000, 2004, 2010, 2012, 2018, and 2023.

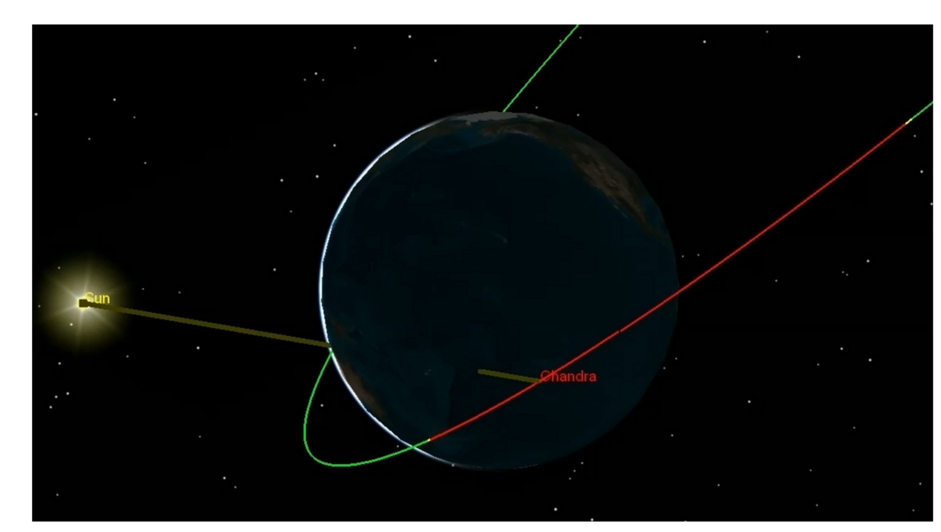


From this we see the stretching, widening, and gradual rotation of the orbit, as well as the shift of the points of apses corresponding to low perigee periods. The figure to the right shows the evolution of orbit inclination, eccentricity, apogee altitude, and perigee altitude over the course of the mission-to-date. Orbit inclination does not follow a particular pattern, but showed a sharp dip from 2015-present. These changes bring Chandra into especially differing regimes with respect to gravity gradient torques and radiation zone passages, as well as eclipse occurrences and durations.



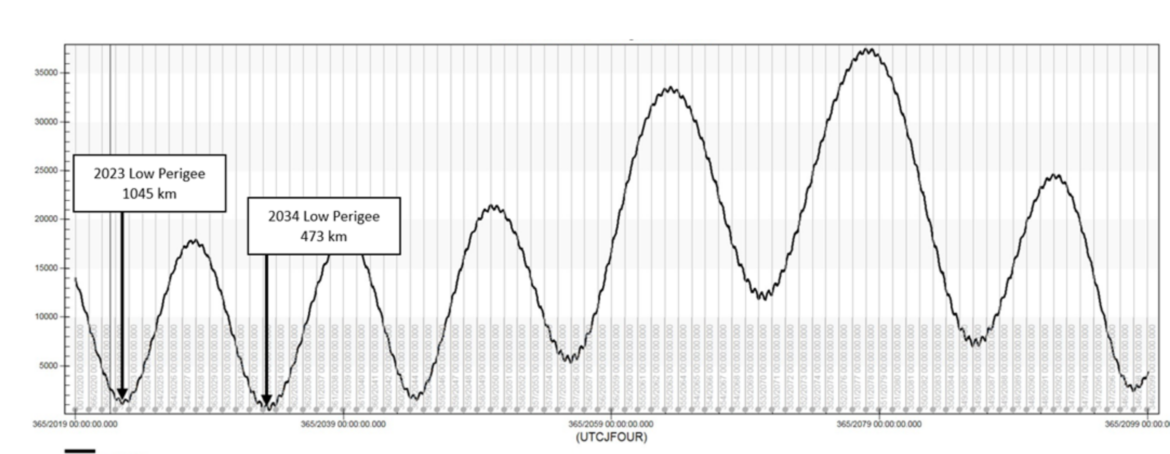
In 2007, it was found that in 2012 the radius of perigee would reach a substantially lower point than had been previously experienced, estimated to be around 3,500 km, bringing with it a need for operational changes due to greatly increased angular momentum accumulation. The new minimum altitude of 3,408 km was reached on July 2, 2012. Leading up to and following this event came several effects, both expected and unexpected, and was met with its own operational changes and lessons learned. Mission Planning guidelines were implemented in response to a few of these unexpected effects, as well as flight notes to technical issues. These impacts were studied and analyzed in preparation for the next low perigee event, predicted to occur in July of 2023.

This was indeed the case, with perigee altitude dropping down to 1,045 km on July 16, 2023. Predictions show that the next lowest perigee, set to be in 2034, will be the lowest point of the entire mission to that point and for decades moving forward. The team has worked to capture lessons learned to prepare for this event, just as was done leading up to 2023.



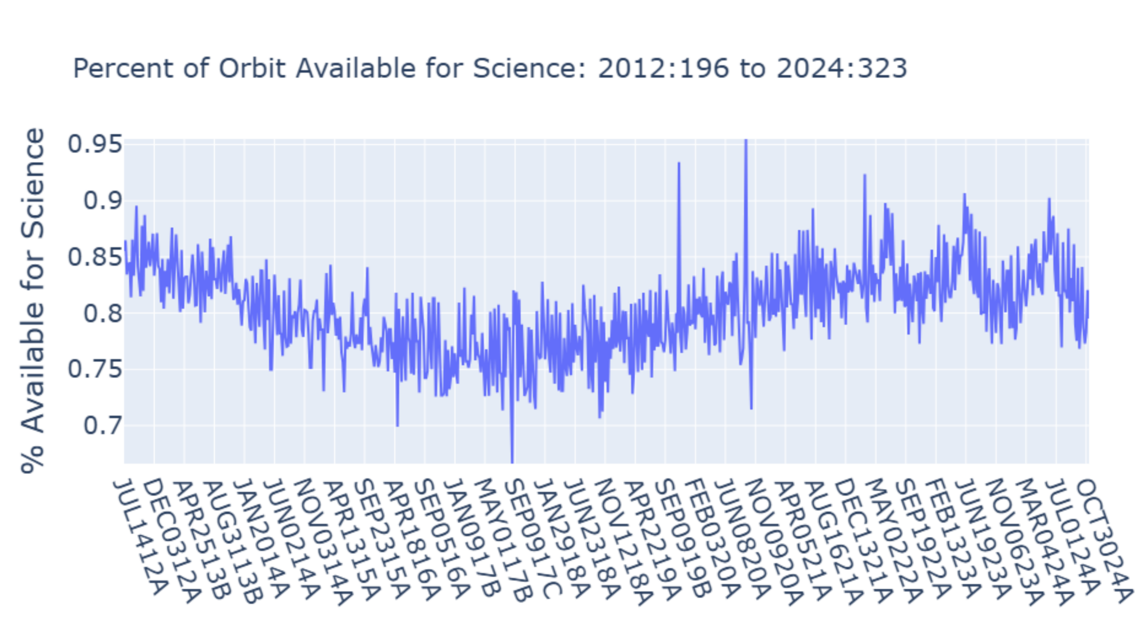
The figure above shows how the position of Chandra's orbit, coupled with the time of year, can result in relatively longer periods of shadowing. Here, a yellow line indicates the vector from the sun to the spacecraft, and the red part of the orbit track is the section in which Chandra is eclipsed by the Earth. Luckily, these only occur at non-observing altitudes. This was from an eclipse season in early 2024.

Analysis has been conducted for the long-term future, past any reasonable end of mission, for decommission purposes. It was found that the spacecraft would not re-enter the atmosphere within the next 100 years while on its current trajectory, with perigee altitude shown below in that time frame.



25 Years Later

Looking back to the initial conditions that the orbit was designed to satisfy, Chandra achieved its goals for the 5-year mission lifetime. From 1999 through 2004, there were no eclipses that exceeded a duration of 2 hours, spacecraft perigees exceeded 9,000 km, increasing to exceed 25,000 km, and Chandra was visible to the DSN for 92% of the 5-year period. But these parameters were set with the stated mission life of 5 years in mind; how has Chandra performed to date? At the time of writing, eclipse durations have still not exceeded 2 hours, with the longest eclipse of the mission actually occurring in 2002 at 92 minutes. The average eclipse over the mission to date is just 15 minutes, for a total time of 461 hours of shadowing over 25 years (0.2%). Perigee altitudes, while having reached minimums in 2012 and 2023 as low as 1,045 km, have still spent a majority of the mission well above the 9,000 km limit; not until 2010 did it drop below it for the first time.



DSN visibility has also remained very strong, with average gaps in coverage actually decreasing for the 20 years beyond the mission life.

On average, Chandra has been in view of a DSN site for over 23 hours at a time, resulting in 94% (~8,655 days) of the total mission time (~9229 days) with visibility, and just 574 days of cumulative gap time. The longest gaps are over 7 hours; however, over two-thirds of them are under 2 hours and the average gap is just 1.5 hours. These statistics continue to underscore the strength of the orbit design and those who crafted it, greatly contributing to the success of a mission 5x its original design, with no end in sight.

To that end, the operational orbit regime has allowed for between 75% and 85% of the orbital period to be available for science from mid-2012 (when data began to be collected) through mid-2024. Often, that percentage is even higher, as shown in the figure to the left. These results give Chandra engineers and researchers alike the confidence that the Observatory will continue to be available for science at a high level for many years to come.

25 years of Science with Chandra - 2024 December 3-6

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