Research Paper / Articles de recherche

The Discovery, Orbit, and Upcoming Close Earth Encounter of Asteroid 887 Alinda

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Abstract

Asteroid 887 Alinda was discovered by Max Wolf at Heidelberg in 1918. Alinda, the second-known, near-Earth asteroid, aroused considerable interest and some confusion at the time. The discovery circumstances are examined with an aim to clarification, including the possible detection of a satellite in follow-up observations. Alinda is also the namesake of a small group of asteroids that orbit the Sun three times per Jupiter orbit, and thus are in 3:1 mean-motion resonance with the planet, in a Kirkwood gap of the asteroid belt. These asteroids are also approximately resonant with Earth, and can make close approaches that are potentially hazardous. Their sidereal period is about four years, but close approaches to Earth usually take place less frequently than that. Alinda had one set of approaches near the time of discovery, one set in the 1970s, and will have another set in the 2020s, including one very favourable approach for its investigation by telescopes, radar, and possibly spacecraft in 2025. An asteroid on a similar orbit, 4179 Toutatis, has recently been investigated in detail.

Résumé

L'astéroïde 887 Alinda a été découvert par Max Wolf à Heidelberg en 1918. Il est le deuxième reconnu parmi ceux qui se rapprochent de la Terre et il a suscité beaucoup d'intérêt lors de sa découverte, en plus de la confusion. Les circonstances de cette découverte sont examinées dans le but de la clarifier, en prenant compte d'une détection soupçonnée d'un satellite durant des observations plus récentes. Un groupe d'astéroïdes qui orbitent le soleil trois fois pendant une période orbitale de Jupiter porte aussi le nom d'Alinda et, dans une lacune de Kirkwood, est en résonance de mouvement en moyenne de 3:1 avec cette planète. Ces astéroïdes sont aussi en résonance approximative avec la Terre et certains d'entre eux peuvent présenter des approches hasardeuses. Leur période sidérale est près de 4 ans, mais normalement ils s'y rapprochent moins fréquemment. Une période d'approche d'Alinda a eu lieu lors de sa découverte, ainsi que durant les années 1970, et aura de nouveau lieu durant les années 2020. L'investigation de son approche très favorable en 2025 sera alors alors entreprise par télescope, par radar et peut-être même par sondes spaciales, tout comme s'est récemment produite pour celle de l'astéroïde 4179 Toutatis, en orbite semblable.

1. Introduction

The first asteroid, 1 Ceres (now designated a dwarf planet), was discovered on 1801 January 1 (Cunningham *et al.* 2011; Foderà Serio 2002), between Mars and Jupiter, in a region of the Solar System that was, in that era, expected to contain a planet. Subsequent discoveries in the 19th century made it clear that a large group of small bodies existed in that zone, which was called the "asteroid belt." According to the tabulation of Tholen (2006), 463 asteroids were discovered in that century (including the year 1900). The Königstuhl Observatory (Landessternwarte), on the small mountain of the same name overlooking Heidelberg, was among the foremost in the world in asteroid discovery in the late 19th and early 20th centuries due largely to advanced photographic and search techniques (Freiesleben, 1962) developed by its eventual director, Max Wolf (1863-1932). The equipment included large refractors and the Waltz 28-inch (72-cm) reflector, a capable instrument in an era of rapidly growing apertures. By the end of 1917, 919 asteroids had been discovered, of which 367, or an astonishing 40 percent, had been netted at Heidelberg. In turn, nearly 54 percent of these had been discovered by Wolf, a very active observer. By early 1918, however, almost all known asteroids were in the asteroid belt.

One exceptional group of asteroids had already been discovered by Wolf. These were the Trojan asteroids, which follow the orbit of Jupiter. In 1906 and 1907, three such asteroids were found (Connors *et al.* 2014). Their exceptional nature was noted on the night of discovery (Wolf 1906) of the prototype, 588 Achilles, since, according to Kepler's third law, the large semi-major axis a results in slow motion through the sky and, in turn, a trail produced on a survey photographic plate that is shorter than those of asteroid-belt objects. The simultaneous assignment of the names Achilles, Hektor (now Hector), and Patroclus, heroes of the Trojan War (Wolf & Kopff 1907), was *de facto* recognition that these objects were different from most asteroids. This grouping appeared to be confirmed by the discovery on 1908 March 23 of 659 Nestor (Wolf 1908), soon suspected (Ebell 1908) to be associated with Jupiter. Nearly ten years were to elapse before the discovery of the next Trojan asteroid. 1917 CQ was found on 1917 September 22 and measured to have slow motion on subsequent nights (Wolf 1917). It was later named 884 Priamus, after the king of Troy. Wolf photographed it on 1918 January 3 (Wolf, 1918) with the 28-inch Waltz reflector and then proceeded to use the smaller Bruce telescope for the latter part of the night, in a survey that discovered a new class of asteroid, as described below.

Only one other asteroid besides the Trojans had been found outside the main belt as of 1918. 433 Eros was discovered on 1898 August 13 by Witt (1898) in Berlin. Some aspects of the discovery are confused (Scholl & Schmadel 2002), but an editor's annotation attached to Witt's notice makes it clear that the object's large motion in right ascension (29′ daily, as opposed to more typical values of 1-2′) made following it desirable. The first known asteroid to come inside the orbit of Mars, Eros was quickly realized to be very valuable in solving the long-standing problem of converting the relative scale of the Solar System into accurate absolute units (Payne 1900), that is to say, determining accurately the value of the astronomical unit (au) in km. The discovery elicited a large amount of interest, and although Eros does not come particularly close to Earth by modern standards, a new class of object, the near-Earth asteroids, was introduced. From an observational point of view, Wolf had found the distant Trojans through careful attention to short trails on survey photographic plates, and Eros made observers alert that there could be long trails also, indicating very nearby objects. Wolf in particular was alert in examining Bruce telescope survey plates, and this paid off on 1918 January 3.

Figure 1 — One of the two original 40-cm aperture f/5 Petzval objective lenses of the Bruce double astrograph. The design consists of four lenses in groups of two. These lenses operated between 1900 and 1950, and allowed the discovery of nearly 500 asteroids (photo by author).

2. Discovery of Alinda

The success of the Landessternwarte was in part based on cutting-edge equipment. Wolf had obtained funding from American heiress Catherine Bruce to develop a specialized double astrograph. This consisted of twin 40-cm aperture (Figure 1), 200-cm-focal-length telescopes imaging onto photographic plates with a field of view 6° by 8°. A separate visual guiding telescope had a 25-cm aperture and 400-cm focal length (Figure 2). Normally, both cameras were active, sometimes with a time offset so that asteroid motions could be determined quickly. The Bruce astrograph came into use in 1900, supplanting an earlier astrograph that had been Wolf's personal instrument. It was used, for example, for the discovery of Trojan asteroid 588 Achilles (1906 TG). Shortly after this discovery in early 1906, the Waltz 72-cm reflector (Figure 3) came into operation. It was financed by Frau K. Bohm (maiden name Waltz) and was a fast f/4 optical system made by the Carl Zeiss Corp. in Jena, with a 20-cm guide telescope of roughly the same focal length, on a massive fork mount. Both telescopes are still present in their domes on top of the Königstuhl, and their plates and logbooks are available on the Internet (see Acknowledgements). Perhaps not surprisingly, the first attempt at asteroid imaging with the Waltz reflector was of 1906 TG (by then numbered 588, but still without a name), with note "TG gefunden" (TG found), on 1907 January 22, eleven months after its discovery.

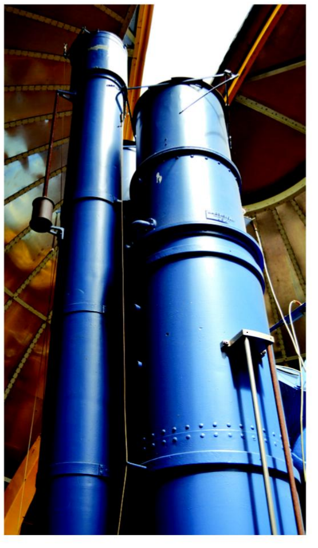

Figure 2 — The Bruce double astrograph in its original dome at the Landessternwarte Königstuhl. The guide telescope is to the left, with one astrograph clearly visible on the right, and the second slightly visible in the gap (photo by author).

By 1918, the operations of the Landessternwarte were highly optimized for asteroid research, with the Bruce double astrograph used primarily in a search role and the Waltz reflector, with its larger aperture and smaller field of view, being used for followup and precise position determination. Both were used in photographic mode. Reduction of data was done with methods developed by Wolf, including stereoscopic techniques with an instrument he helped to develop. Theoretical work on asteroid orbits was being developed simultaneously, largely at other institutions. Orbit determination was very important so that objects could be located again in the future, and this relied not only on obtaining sequences of follow-up observations, but also on good fits to the data, taking into account planetary perturbations.

Alinda first appears as a footnote in a list of observations of asteroids on 1918 January 3 in the *Astronomische Nachrichten*, Number 4922 (Kobold 1918a). It states that "the nature of this object on the edge of the plate cannot be determined with certainty. The motion is only approximately given; it is perhaps larger than given. The position angle of the motion is 204°. The direction of motion may be reversed." The motion referred to was mainly in declination, inferred as −66′ per day, and the magnitude was estimated as 11. This fast-moving, bright object clearly elicited immediate interest; however, the unfortunate

Figure 3 — The Waltz reflector of the Landessternwarte Königstuhl, with 72-cm mirror by Carl Zeiss, Jena. The telescope has an f/3.9 primary mirror. Its light-gathering power, although with a smaller field of view than the Bruce astrographs, made it ideal for asteroid followup after its construction in 1906. The telescope has been converted to a Nasmyth-Cassegrain with a secondary mirror near the entrance (top) and a tertiary mirror directing light to instruments along the declination axis (lower right). Photo by author.

location near, and going off, the edge of plate B4031a (which is damaged and was scanned in support of this article) made further searching difficult, as may be imagined by examining Figure 4. Even worse, the twin plate B4032b, which would normally have allowed verification of the reality of a faint asteroid trace, did not completely overlap with the discovery plate, and did not show the long trace. Wolf's subsequent recovery strategy can be deduced from observing logs available online. Despite the long trace, Wolf's first attempt at finding the object again was to take an exposure adjacent to where it had initially been seen. Presumably due to bad weather, this plate was not taken until January 8.

Kobold had noted in *AN* 4922 that there had been a report the previous month (Kobold 1917) of an unconfirmed possible comet relatively distant in the sky from the discovery location. This seems to have motivated a search along the extension of that path, on January 14, with exposures over three hours long (plates B4035, B4036). This path would have corresponded to a negative declination motion. A second pair of plates (B4037, B4038) was taken the same night in a location that would have reflected positive declination motion from the discovery location, along the direction of the long trace. These plates were exposed for roughly two hours. One must also bear in mind that, unlike modern CCDs, plates had to be developed. Wolf would not know until the next day that neither pair of plates had succeeded in finding the object. Some plates taken January 28-29 were for unrelated projects, since the full Moon interfered with asteroid searching.

On January 30, an early evening plate pair looked in a region not clearly related to the new object. The Moon then rose, presumably precluding further searching. On 1918 February 2, the search resumed close to the area indicated by the discovery plate if the declination motion had been northward but slow (plates B4045, B4046). Finally, on February 3, the object was found at a yet more northerly location. A repeat exposure was made on February 4. These four plates, each with a three-hour exposure time, were B4047 through B4050. On February 5,

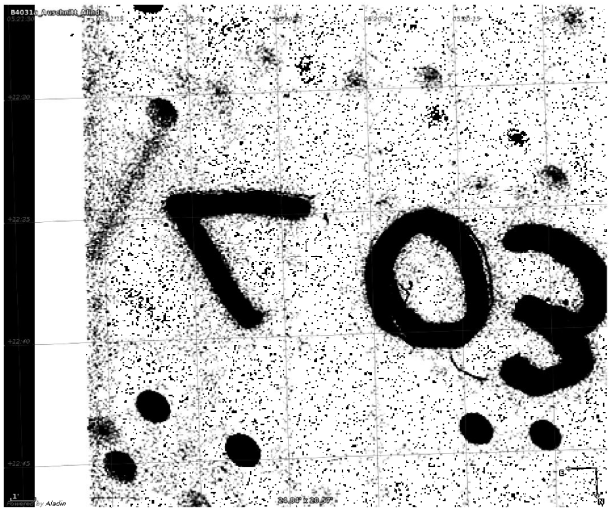

Figure 4 — Alinda's trace on the discovery plate taken on 1918 January 3. A leftward pointing arrow written in ink points toward the trace, which begins at a star and moves northward (downward). The star directly below this mark is on the edge of the twin plate. J2000 coordinates are overlain and the contrast has been enhanced. The exposure time was 2.5 hours.

the Bruce astrograph returned to its normal search for new asteroids, while the Waltz reflector took over following the object, which the recovery by the Bruce astrograph allowed to be found within its smaller field of view. The object was denoted Planet-Comet 4031.03 in the observing log, this designation from the number of the discovery plate. The exposures tracked its motion, resulting in a point-like asteroid in a field of trailed stars (Figure 5). A notation was made of the need to turn the guiding rod every minute because of the object's rapid motion. The larger Waltz reflector aperture allowed the exposures to last only 30 minutes each and motion to be seen between them.

The recovery by Wolf was announced by the *AN* editor (Kobold 1918b) as the first of several short articles filling three pages of the journal. Several days of observations, up to February 14, were provided from several observatories, and preliminary orbit determinations and ephemerides given. The "remarkable celestial body" was provisionally named 1918 DB and referred to as the "*Wolf*sches Gestirn" (italics those of *AN*). As imaged on 1918 February 5, it showed no gas shell, and so was not a comet. Incredibly, Wolf announced that it appeared to be accompanied by a satellite. This may be seen on the superposed plates shown in Figure 5, with motion between the time of the plates. In hindsight, we may realize that if a satellite had been slowly moving around Alinda, its traces would have been lengthened and not pointlike. The marks may have originated in defects that were unfortunately positioned on the two subsequent plates. None of the many other images of Alinda showed any evidence of a satellite. Many asteroids are now known to have satellites, although

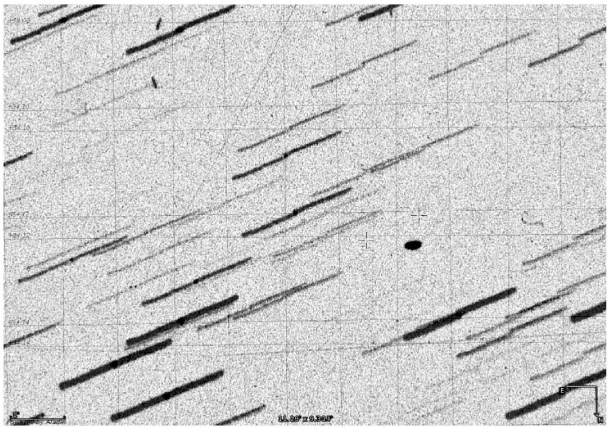

Figure 5 — Alinda on the first plates showing it with the Waltz reflector, which have been digitally superposed. Alinda is at middle lower right as a spot. The two marks from the suspected satellite are in the upper left. All other features are trailed due to tracking at the rate of the asteroid. Double grids in J2000 coordinates are shown.

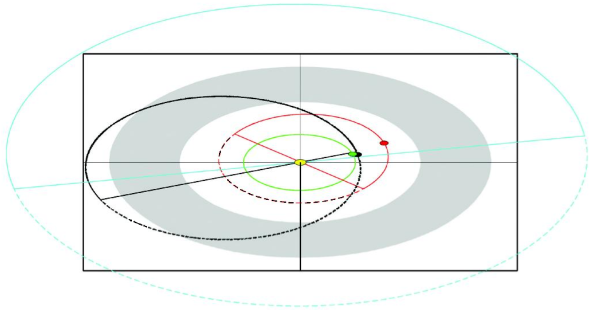

Figure 6 — Orbits and positions relevant to Alinda's close encounter with Earth on 2025 January 8. Orbits are shown with dashes when below the ecliptic, and solid when above. The vernal equinox is toward the bottom and a grid with spacing 3.885 au is shown. The orbits of Mercury and Venus have been omitted for clarity. Those of Alinda (black), Earth (green), Mars (red), and Jupiter (cyan) are shown, with the positions of the first three shown on the date of encounter. Most main-belt asteroids remain within the grayed region.

this was contentious until the discovery of one in 1993 by the *Galileo* spacecraft; one had even been claimed for Eros in 1901 (Merline *et al.* 2002). In retrospect, Wolf was displeased by his rapid but erroneous conclusion, by now published. Freiesleben (1962) quotes from his diary entry of 1918 February 15, referring to the satellite finding as "The greatest embarrassment of my life???" and Alinda as "a completely ordinary asteroid with large eccentricity," concluding "I am condemned!"

In any case, the recovery observations were now consistent with the observations on 1918 January 3, which thus were now referred to as the "discovery exposures." It was possible to conclude that the large-eccentricity object (in fact a parabolic approximation was used for the orbit) had been at its node and also at perihelion very close to the discovery date, and been only 0.2 au from Earth at the time. This explained the rapid motion of the object when detected. With these observations, the presence of a second near-Earth asteroid was affirmed.

3. Alinda's Orbit

Thanks to Wolf's rapid work in following up Alinda, basic details of its unusually eccentric near-Earth orbit were already clear in 1918. Its physical nature was not determined until much later observations (Veeder *et al.* 1989) gave a diameter of 4.2 km, visual albedo 0.23, and a common inner-Solar System type of S, meaning a stony asteroid. These values are based on 10μ infrared observations from Mauna Kea. This relatively large asteroid (among near-Earth types) does not cross Earth's orbit, but its orbit is changing in such a way that it will.

The orbital configuration at the upcoming close encounter of Alinda with Earth on 2025 January 8 is shown in Figure 6, and its recent orbital elements are given in Table 1. Alinda has an inclination of i = 9.36°, and thus spends most of its time out of the plane of the ecliptic. For example, the orbit passes above and below that of Mars, and it also traverses the asteroid belt non-centrally. Its inner node is very close to its position at perihelion, and this in turn is only about 0.1 au outside Earth's orbit, and when it does line up with Earth in the manner shown, this is roughly how far away it is. At the present time, close encounters with Earth do not greatly affect its orbit, and orbital change is mostly caused by Jupiter.

The eccentricity of the orbit (e) is 0.5675, which means that the object goes out past most of the main belt, but not far enough out to have close encounters with Jupiter. Its semi-major axis (a) is 2.4784 au, resulting in a period of 3.90 years. A rough idea of the geometry relative to Earth can be had by reasoning that the position of Earth would be the same as in

Element	Value	Uncertainty (1-sigma)	Units
e	.5674585315701524	5.4245e-08	
a	2.478434474102797	1.8393e-08	au
q	1.072025686835581	1.3747e-07	au
i	9.359372430222889	7.6642e-06	deg
Ω	110.5521543922645	3.6085e-05	deg
ϖ	350.3383965724346	4.0788e-05	deg
M	149.3667119772119	3.8028e-05	deg

Table 1 — Standard orbital elements of asteroid 887 Alinda for epoch Julian Day 2457000.5 (2014 December 09.0) in heliocentric ecliptic J2000 coordinates. Elements not identified in the text are Ω, the longitude of the node, ϖ, the argument of perihelion, and M, the mean anomaly at the epoch. From http://ssd.jpl.nasa.gov/sbdb.cgi?sstr=alinda&orb=1, cited 2015 January 29.

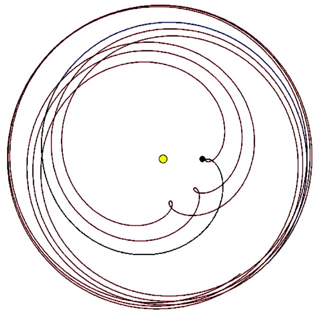

Figure 7 — Clockwise motion of Alinda in a frame co-rotating with Earth from 2014 August 8 to 2026 August 8. Relative motion in the year 2025 is shown in black, and in 2026 in blue. Earth (blue dot) is 1 au from the Sun (yellow dot).

Figure 6 if a time one year later was plotted. The asteroid would move more than one-quarter way around its orbit by that time, since Kepler's second law has it moving faster when near perihelion. One year more, and Earth would again be in the same place, but Alinda near aphelion. One year more, and Alinda would be less than three-quarters of the way through an orbit, having moved slowly when near aphelion. And on the fourth anniversary, Alinda would again be near perihelion; however, since its period is slightly less than exactly four years, it would be a bit past perihelion. Gaining on Earth by 0.10 year's motion each four years, but with motion near apogee slow, it takes roughly 50 to 60 years for Alinda to come back to the same position relative to Earth and have a close passage. At the other end of this cycle, approaches of Alinda steadily become more favourable before its next close encounter. Its position relative to Earth from 2014 to 2026 is shown in Figure 7. The cycloidal pattern arises from the asteroid moving in and out on its elliptical orbit, and around the Sun relative to Earth by the process described above. The close approach in 2025 is clear, and this and the previous perihelion passages can be seen as loops in the inner portion of the orbit. In such a diagram, opposition takes place directly to the right of Earth (*i.e.* when the asteroid is on the opposite side from the Sun as seen from Earth). It can be seen that the asteroid is usually far away at opposition, and only at close approach would it be bright. Further, at most perihelion passages, it is not well placed for observation, although in this epoch it is better placed than usual, being closer and thus brighter.

If the orbit of Alinda is plotted with respect to Jupiter, the threefold symmetric path shown in Figure 8 arises. The outer points in this figure arise when the asteroid is near aphelion. The figure is not closed, and slowly reorients itself with respect to Jupiter with a period of about 370 years. This slow motion is referred to as libration. Space does not permit discussing the details here, but Alinda was used as an example by Greenberg (1977). The pattern in the rotating frame, and the libration, are characteristic of 3:1 resonance, but this was not quickly realized.

4. Recognition of 3:1 Resonance with Jupiter

The modern view of our Solar System places a great deal of emphasis on the phenomenon of resonance. Indeed, in the introductory chapter to *Solar System Dynamics* (Murray & Dermott 1999) it is stated that "the subtle gravitational effect that determines the dynamical structure of our Solar System is the phenomenon of *resonance*" (italics those of the authors). We now have access to information about many more planetary systems, and this statement applies to many of them as well (Zhang *et al.* 2014). The importance of resonant phenomena was already pointed out by Brown (1911a), attempting to give a theoretical basis to the gaps in the asteroid belt's distribution of semi-major axes noted by Kirkwood in 1866 (Kirkwood 1888). The theory of resonance was, however, not well developed, as evidenced by Brown's own (Brown 1911b) advancement of the three-body problem for 1:1 resonance (relevant to the then recently discovered Trojan asteroids) through an essentially geometric argument based on 18th-century work of Laplace. Despite Kirkwood (1888) having specifically mentioned the gap at 2.5012 au (significant figures given by Kirkwood) as being related to the fact that "an asteroid's period would be one-third that of Jupiter," the presence of Alinda in a Kirkwood gap, and the fact that it was a Jupiter-resonant asteroid, seems to have gone unnoticed until 1969. E.W. Brown wrote numerous papers after 1911 on Trojans as a resonant system, and discussed the Kirkwood gaps extensively in terms of resonance and high eccentricity. Examination of the papers leading up to his review (Brown 1932) seems to indicate that he did not know of the existence of Alinda, and in fact had last looked at the observational data in 1911 (Brown 1911a)! Schweitzer (1969) referred to the 3:1 gap as the "Hestia" gap, and identified Alinda as being in it. Sinclair (1969) also found this result. Both authors used computers to calculate various orbital parameters through time, and demonstrated libration, an essential characteristic of resonance mentioned in the previous section.

The seeming lack of attention to basic properties of asteroid orbits, such as resonance, seems puzzling to us. In recent years, we have easy access online to tens of thousands of very well-determined asteroid orbits and hundreds of thousands of good ones. We can easily look for interesting orbits to study, and we can do meaningful statistical studies. It was not always so! It was noted above that a driving force behind major observational and data reduction efforts was determination of asteroid orbits with high precision, so that the growing number of them could be followed and so that they could be found again after passing close to the Sun in the sky. The

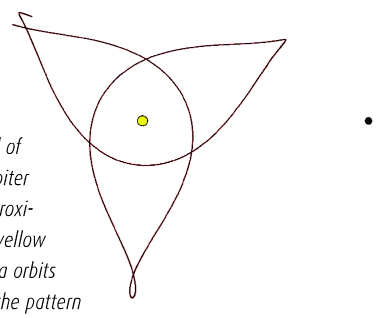

Figure 8 — Counterclockwise motion of Alinda in a frame co-rotating with Jupiter from 2014 August 8 to 2026 August 8, which is approximately Jupiter's period of revolution around the Sun. Jupiter is indicated by a blue dot approximately 5.2 au from the Sun (yellow dot). During this period, Alinda orbits the Sun three times, making the pattern relative to Jupiter shown.

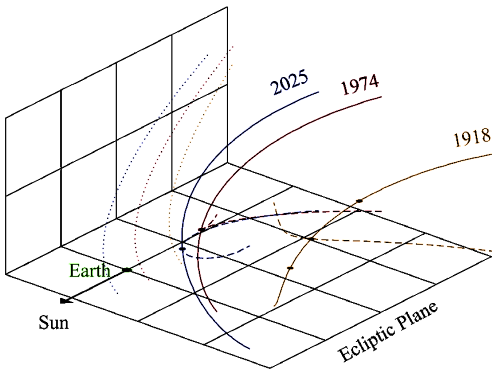

Figure 9 — Motion of Alinda in its 1918, 1974, and 2025 passes, relative to Earth (green dot). Each square is 0.1 au on a side and the arrow points to the Sun. At this scale, the orbit of the Moon is smaller than the dot indicating Earth. On all traces the motion of Alinda is toward the year marker. Dots indicate where Alinda crosses the ecliptic. In 1918, the dot below the ecliptic plane is for the 1918 January 3 discovery date, and the dot above the plane is for the 1918 February 3 recovery date. Dashed lines show the projection of the path into the ecliptic plane. Alinda was discovered below the plane but near closest approach to Earth in 1918. Dotted lines are projected onto the perpendicular plane to the ecliptic, and the relative motion rises quickly above it.

importance of the ability to "recover" an asteroid was made clear already in 1801 and 1802 when the first of them was lost in solar glare almost immediately and only recovered through the application of the prodigious theoretical skills of Gauss (Cunningham *et al.* 2011). The need to represent orbits accurately led to orbit determination becoming a highly specialized branch of mathematics. A good illustration of that in the present context is a series of papers by Stracke (1933, 1936) and Steinmetz (1941). In the first of these, Stracke emphasizes that "among the minor planets discovered by Wolf, Alinda is, next to the Trojans, the most unusual find." He noted that several large-eccentricity asteroids (among them 719 Albert, discovered before 887 Alinda) could only be observed near perihelion due to being faint, and that this made approximate methods of orbit determination unsatisfactory to ensure their recovery from year to year. Further, Albert had been lost despite having been named and numbered (requirements for this are now much stricter). It was clearly known to be an interesting object, and of high eccentricity, but Alinda was of greater interest, in part because its orbit had been well determined through the efforts of Wolf. Stracke noted that Albert might be found in the future, but only by chance; in fact this happened in the year 2000 (Tsiganis & Varvoglis 2000). To ensure that Alinda did not eventually suffer a similar fate, he proceeded to produce the best ephemeris possible, asking observers to be sure to recover it in 1933–1934, in the face of the fact that each opposition saw it farther from perihelion and fading in brightness (see discussion of the orbit above). The effort was successful, and he was able to conclude his 1936 article by stating that "the result of the orbit determination of 887 Alinda came out so well, that we can presently say that it can be counted among the asteroids whose orbits are the most reliably determined." Noting the deteriorating observational situation, and asking southern observatories in particular to help, Steinmetz (1941) gave details about the mathematical precision required and the high order of terms added to series representing perturbations from planets. These heroic efforts did pay off in that the unusual minor planet Alinda was never lost.

On the other hand, our developing modern view of celestial mechanics allows some insight into the basic nature of the problem of orbit determination for certain asteroids, and in particular resonant ones. In the lecture given in appreciation of the American Astronomical Society's Urey Prize, Wisdom (1987) pointed to developments in chaos theory during the 20th century that showed that averaging (an essential element in development of series solutions such as those used in the classic approach to the orbit of Alinda) could not be guaranteed to give convergent results in all circumstances. In the case of small perturbations, they usually would. In the case of eccentric orbits and with resonance playing a role, convergence was not even likely, or could happen at some times, and seemingly inexplicably not at others. He specifically gave examples from his work on the 3:1 mean motion resonance, in which Alinda is found. Chaotic effects in these strong resonances can give rise to an increase in asteroid eccentricity, which is what has brought Alinda from the asteroid belt to our vicinity.

5. Close Encounter in 2025

Alinda was discovered at about 11th magnitude when making a near-Earth opposition at a distance of 0.216 au in 1918 (it had been slightly closer in 1914). Only one other favourable opposition took place in the 20th century; Steinmetz (1941), for example, referred to the deteriorating observational situation in its first half. In 1970, it passed 0.229 au away and in 1974, 0.137 au away, with a maximum brightness of about V=10.6 in 1974 that permitted photometry to be done (Dunlap & Taylor 1979). This photometry revealed the longest then-known period of rotation among asteroids, 74.0 hours, with an amplitude of about 0.3 magnitudes.

On 2025 January 8, Alinda will make its closest approach to Earth in the 20th or 21st centuries, at 0.0822 AU. The circumstances for this and previous encounters are shown in three dimensions in Figure 9. The projection of the 2025 encounter into the ecliptic plane corresponds to the small loop near Earth shown in Figure 7, but this view makes the rapid motion upward out of the ecliptic plane clearer. A few days after closest approach, its magnitude should be 9.0, much brighter than it has been since its discovery, and it will be at favourable northerly declinations. This should present good opportunities for observation, including by amateurs. An even more intriguing possibility is that a space mission could be developed to take advantage of this unique opportunity.

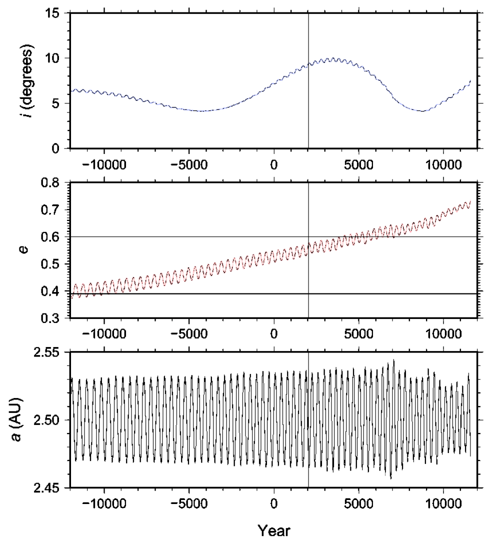

Figure 10 — Orbital elements of Alinda over 22,000 years. The semi-major axis (a) (bottom panel) does not change appreciably over the long-term, but varies with about a 370-year cycle due to libration. The inclination (i) (top panel) remains moderate during this period. The eccentricity (e) (middle panel) rises steadily, causing planetary crossing, with the bottom horizontal line indicating average Mars crossing, and the top (e = 0.6) line Earth crossing. Once Earth crossing begins, a variations become more irregular due to close encounters. Vertical bars in each panel indicate the year 2014.

The asteroid 4179 Toutatis shares some orbital characteristics with Alinda, including being in the 3:1 resonance at high eccentricity. Its perihelion distance (*q*) brings it slightly inside Earth's orbit, and its period of 4.03 years has led to a series of close-Earth passages in recent years, allowing its study by radar and optical means, and culminating in the Chinese *Chang'e-2* spacecraft flyby (Huang *et al.* 2013). Toutatis has, in the past, been described as "potato-shaped" and now is described as "ginger-shaped"; in either case, it is an intriguing highly elongated body, with a rotation period of 5.4 days (longer than the ≈3 days for Alinda). Much information about the elongation of Toutatis was initially derived from light curves (Spencer *et al.* 1995) with an amplitude of 1.2 magnitudes. Further, the spin state is one of "tumbling." In preparation for a possible Alinda mission, verification of its spin parameters would be a desirable objective. Unfortunately, its typical magnitude in the next few years is fainter than 18, making this a task for a large telescope. If the spin period is in fact long, a further problem is that a large time allocation would be needed. Nevertheless, the much lower amplitude of the light curve as compared to that of Toutatis suggests a less elongated body and likely a simpler rotation state.

A flyby mission similar to that for Toutatis described by Huang *et al.* (2013), with more detail provided by Liu *et al.* (2014), is likely within the scope of a nation with space capabilities at the level of Canada's. Launch services would need to be obtained from another country. Since Alinda would be near Earth, considerably lower telecommunication power would be needed than for a deep-space mission such as *Dawn* (Russell *et al.* 2007), especially as such a mission would be operating in the asteroid belt and more solar power would be available. The change in velocity needed to have a slow rendezvous with Alinda would be comparable to what *Dawn* had to achieve in getting to Vesta. A mission with similar ion propulsion could conceivably lead to a view very close to the asteroid lasting several weeks, or possibly a landing. Extrapolating from Figure 7, it is clear that rendezvous with Alinda is a once-in-a-lifetime opportunity for study of an object whose characteristics remain poorly known. Other stony asteroids visited by spacecraft, like Toutatis, have been elongated and heavily cratered. We may be able to find out whether the low-amplitude light curve of Alinda means that it has had a different collisional history, if we can observe the degree of cratering or other deformation.

6. Discussion

The systematic search program at Heidelberg, using the world's most suitable optical equipment, led Wolf not only to dominate the discovery of main-belt asteroids in the early part of the 20th century, but also to discover at least two new classes of asteroidal motion, the Trojans and Alindas. The latter was due to vigilance in looking for unexpected objects and a follow-up program that also served to determine orbits more precisely to allow recovery of newly discovered objects in the following year. Perhaps the rigours of this task, and the attention paid to enhancing predictive models, led to the resonant properties of the new classes taking a long time to find, with Alinda's relationship to Jupiter not recognized for about 50 years after its discovery.

The 3:1 resonance, for which Alinda is the prototype, is now recognized as an important source of near-Earth asteroids, many of which have collided with planets, plunged into the Sun, or been expelled from the Solar System. Calculations based on the Mercury integrator (Chambers 1999) show that Alinda itself will cross Earth's orbit starting in about 3000 years (Figure 10). Resonance chaos effects (Wisdom 1987) impose the steady increase in eccentricity that will bring this about, superposed on the short-term (370-year period) variation mainly due to libration (Greenberg 1977). Our ability to predict orbits in detail is limited by the chaotic effects, so that we cannot say what the long-term fate of Alinda will be, and a future collision with Earth cannot be ruled out, although it is not possible now. A recent development, arising from the ability to compute close encounters accurately, is that 3:1 asteroids can be "flipped" into a retrograde orbit (Greenstreet *et al.* 2012). Some likely candidates for this have been observed among the near-Earth asteroid population.

Alinda serves as a prototype for resonant asteroids in general, with the understanding of resonant behaviour now enhanced through the application of the tools of chaos theory. By 2018, the centennial of its discovery, it would be fitting and useful to be preparing once again to apply the world's most sophisticated techniques of asteroid research by preparing a space mission to visit it. ✶

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On Special Epochs, the Copernican Principle and Future Astronomy

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Abstract

The history of astronomy teaches us that many special epochs have occurred in the past. Indeed, it is at these exceptional moments that rapid changes in technological advancement and/or theoretical understanding take place. These transitory epochs are literally the "anchor points" of human intellectual development. Building upon the idea of expeditious, yet transitory, developments in astronomy, this essay explores the timeline that has resulted in humanity's ability to measure the size of the observable Universe. Remarkably, we have within the last 50 years attained knowledge of the very limits of observability—a special achievement and epoch, indeed. While the future for astronomical research and new discovery appears as exciting and as large as ever, it is argued that the strict adherence to the Copernican Principle, a philosophical methodology apparently sacred of present, should be abandoned as astronomers contemplate their future research. Additionally, it is argued that the same opportunities that have enabled the most recent opening up of new "windows" through which we can view the Universe do not necessarily exist as we move forward in time, and this begs an analysis of the question apropos the future outlook for observational astronomy.

Résumé

L'histoire de l'astronomie nous enseigne que par le passé il y a eu de nombreuses époques spéciales. En effet, c'est à ces moments exceptionnels que des changes rapides ont lieu en technologie et/ou en notre compréhension de la théorie. Ces époques transitoires sont littéralement les points de repère dans le développement intellectuel de l'homme. Se fondant sur le concepte des développements expéditifs mais transitoires de l'astronomie, cette dissertation explore la période dans laquelle l'homme a pu mesurer l'étendu de l'univers observé. Ce qui est remarquable est que durant les dernières cinquante années, nous avons atteint des connaissances des limites ultimes de l'observabilité—vraiment une réussite et une époque très spéciales. Pour l'avenir la recherche astronomique et les nouvelles découvertes paraissent aussi passionnantes et importantes que jamais. Toutefois nous soutenons qu'une stricte adhésion aux principes de Copernicus, aujourd'hui une méthodologie philosophique d'aspect sacrée, devra être abandonnée lorsque les astronomes considèrent leurs recherches futures. Nous soutenons aussi que les opportunités qui ont permises l'ouverture récente de nouvelles 'fenêtres' à travers lesquelles nous pouvons contempler l'univers ne seront pas nécessairement disponibles à l'avenir. Ceci exige une analyse de la question concernant l'avenir de l'astronomie observationnelle.

1. Introduction

One of the great benefits of teaching a course related to the history of astronomy is that it provides an opportunity to look anew at the subject; to probe the story lines and to re-assess what has been said and done before. I am in the fortunate position to teach such a course every few years, and during the progress of the last offering, the topic of special events and unique epochs gave me specific cause for reflection. While all history is partly about unravelling firsts, who did what and when, the development of astronomy itself, since the mid-16th century, is generally portrayed under the guise of expanding horizons along with the developing concept that humanity, along with the Sun and the Solar System, is not centrally located within the Universe or, indeed, located within any special place at all. This latter idea is usually expressed under the guise of the Copernican Principle, or the Principle of Mediocrity. While Copernicus himself would neither recognize nor appreciate the principle named in his honour, it is the case that the principle has been greatly misused in recent decades. Indeed, it can lead us to wrongheaded ways of thinking about the Universe and humanity's standing within it. As described in an earlier article (Beech 2011), for example, the blind acceptance of the Copernican Principle has resulted in the entirely wrong concept being propagated within popular astronomy texts that the Sun and Solar System are in every way average, even bland and/or typical. They patently are not average in many demonstrable ways, and our seemingly modern fear of allowing for special circumstances and the existence of unique structures, events, epochs and

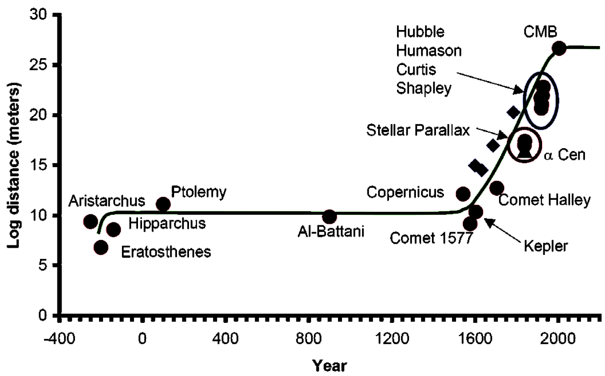

Figure 1 — Estimates to the minimum size of the Universe over recorded history. The vertical scale is expressed as the logarithm of distance measured, in metres. While it may appear that recent history indicates an ever-increasing measure, the cosmic microwave background (CMB) point marks, in fact, the absolute limit of increase at the present time. The "trajectory of knowledge" (solid line) has increased like a logistic curve and we are currently at the special location of the upper turnover point.