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ASTEROIDS IN THE INNER SOLAR SYSTEM

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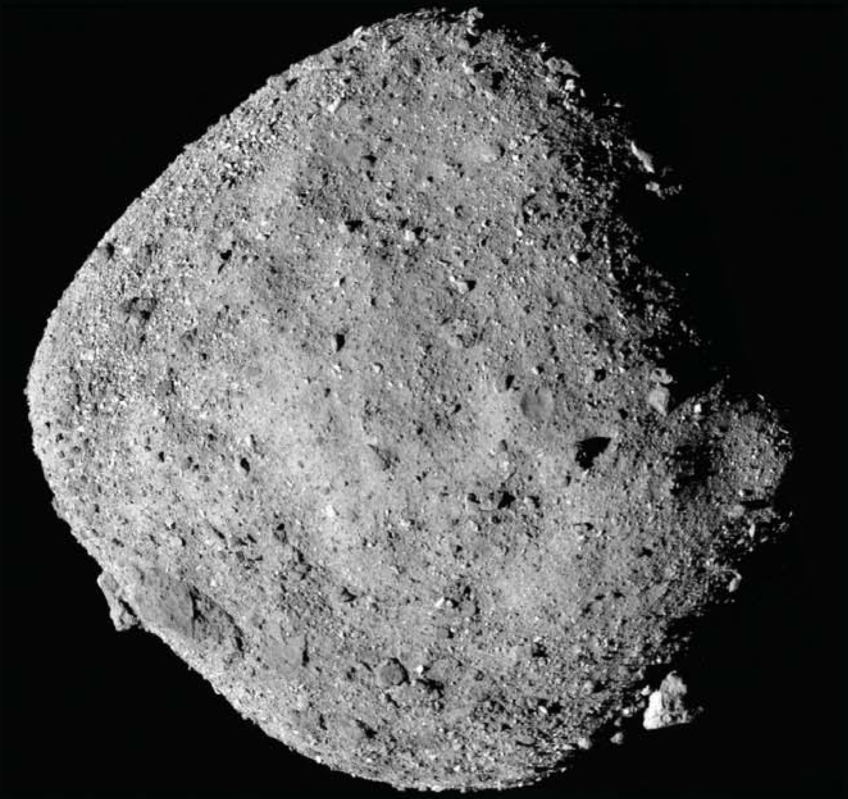

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Observations and computer simulations of their orbits and interactions with planets yield insights into the asteroids' dynamic lives.

About 500 meters wide, Bennu orbits our Sun in the Apollo population of near-Earth asteroids. It was visited and photographed by spacecraft *OSIRIS-REx* in December 2018.

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People tend to think of the solar system as a static environment, in which the orbits of the planets, asteroids, and comets have remained the same over its lifetime. But although its current architecture has existed for roughly the past 4.5 billion years, the solar system is far from the unvarying environment that we imagine.

The gravitational influence of the planets over small bodies, particularly those in the solar system's inner regions, has modified many asteroid orbits in quite dramatic ways. For example, the interactions can push asteroids from nearly circular orbits in the main asteroid belt between Mars and Jupiter to highly elliptical orbits that cross those of all the terrestrial planets. Eventually, those perturbations can move the asteroids' perihelia—their closest orbital distance from the Sun—to within the star's radius. They are known as Sun-grazing orbits. The asteroids' transformation from main-belt orbiters to Sun grazers can take place in the surprisingly short time scale of a million years. That's less than 0.02% the age of the solar system.

In addition to decreasing the asteroids' perihelia, gravitational interactions can also decrease their aphelia—their farthest orbital distance from the Sun—and push them to increasingly smaller orbits. That movement progressively nudges asteroids onto hard-to-reach orbits that are closer to the Sun than either Earth's orbit or Venus's orbit; the asteroids are known as Atiras and Vatiras, respectively. The orbital evolution of those rare Atira and Vatira asteroids is a reminder that their trajectories can change dramatically over their lifetimes and take them throughout the inner solar system. That evolution can tell us where the asteroids have likely been and where they will likely go as their orbits continue to evolve. More practically, it can tell us where to point our telescopes to find those elusive objects.

From main-belt to Sun-grazing orbits

More than 525 000 numbered asteroids with well-known orbits and in sizes ranging over several orders of magnitude—from hundreds of meters to a thousand kilometers—currently inhabit the main asteroid belt. Several basic parameters describe their orbits around the Sun. The semimajor axis refers to an asteroid's average orbital distance from the Sun. That distance is often measured in astronomical units, with 1 AU defined as the mean Earth–Sun distance. The eccentricity is the asteroid's orbital ellipticity. It equals 0 for a circular orbit and 1 for a parabolic orbit, a trajectory whose energy is the minimum required for an asteroid to become unbound from the Sun and escape the solar system. For all values between those extremes, the orbit is more or less elongated. The inclination refers to the orbit's angular tilt relative to the plane of the solar system in which the planets lie.

Figure 1 shows two commonly used projections of the known main-belt asteroids between Mars and Jupiter. Compared with the roughly circular planetary orbits, main-belt asteroid orbits are more elliptical and are inclined by as much as 30°. The first person to arrange the ever-growing number of discovered asteroids by average distance from the Sun was mathematician and astronomer Daniel Kirkwood. Upon arranging the asteroids that way in 1866, Kirkwood noticed sharp drops, now called Kirkwood gaps, in the number of asteroids located at specific semimajor axes. Few asteroids reside in the Kirkwood gaps, and they span large ranges in eccentricity and inclination.

Kirkwood identified the most obvious gaps in the asteroid population at 2.50, 2.82, 2.95, and 3.27 AU as locations of the 3:1, 5:2, 7:3, and 2:1 orbital resonances, respectively, with Jupiter.[1] An orbital resonance occurs when an asteroid's orbital period is an integer multiple of a planet's. For example, the 2:1 resonance with Jupiter occurs when an asteroid orbits the Sun exactly twice for every orbit of Jupiter. Resonances occur at specific semimajor axes because, as Kepler's third law tells us, the square of an object's orbital period is proportional to the cube of its semimajor axis. Thus, because those resonances occur for specific orbital periods, they are located at the corresponding semimajor axes.

Why are so few asteroids located in the resonances associated with the Kirkwood gaps? The main belt hosts numerous orbital resonances with Mars, Jupiter, and Saturn, and several of them overlap in the gaps. The overlapping resonances cause the orbits of the asteroids in the region to be unstable, and the instability leads to an excitation, or increase, in asteroid eccentricities. The semimajor axis of an asteroid in a resonance cannot itself change, so as the asteroid's orbit evolves, its eccentricity follows a vertical path from low to high values in the plot of eccentricity versus semimajor axis (see figure 1b). Eventually, the eccentricity reaches values larger than the moderate eccentricities seen in the main belt.

As an asteroid's eccentricity increases, its orbit becomes increasingly less circular and more elliptical. The elongation causes the asteroid's perihelion to decrease and its aphelion to increase, eventually putting the asteroid on a terrestrial planet-crossing orbit. If the orbit becomes so highly elongated that the perihelion drops to within the solar radius, the asteroid reaches a Sun-grazing orbit and incinerates during its next perihelion passage. Over time, the resonant-eccentricity-excitation process has nearly emptied the Kirkwood gaps of asteroids as they are transported from the main belt to the inner solar system.

How long does it take for an asteroid orbit to be altered from main-belt to Sun-grazing? A landmark study performed by Paolo Farinella and colleagues in 1994, when Farinella was a visiting professor at the Nice Observatory in France, found that low-eccentricity asteroids located in a resonance with a planet can evolve onto Sun-grazing orbits in as little as 1 million years.[2] Over the past 4.5 billion years of solar system history, asteroids located along the borders of those resonances have slowly diffused into the resonances and supplied at a steady rate the sunward transportation of asteroids from the main belt.

That slow diffusion most frequently occurs through gravitational close encounters with the planets, which can change an asteroid's semimajor axis. Just as a spacecraft can gain or lose speed by passing closely behind or in front of a planet, so can an asteroid. Because orbital speed is inversely proportional to orbital period and the period squared is proportional to the semimajor axis cubed, an increase in orbital speed causes a decrease in semimajor axis and vice versa. Planetary interactions can thus change the semimajor axis of an asteroid located just outside the border of a resonance enough to move it into the resonance.

Near-Earth asteroids

Not all asteroids in resonances reach Sun-grazing orbits. Once an asteroid's eccentricity increases enough, a gravitational close encounter with a planet can move the asteroid out of the resonance. The interaction leaves the asteroid on a planet-crossing orbit that is no longer on a resonant path to a Sun-grazing orbit. Because orbital periods close to the Sun are quite short, the asteroid experiences frequent planetary close encounters once it reaches terrestrial planet-crossing orbits. Each encounter causes a small change in the asteroid's semimajor axis, and frequent encounters scatter asteroids throughout the inner solar system. The process feeds the population of what are called near-Earth asteroids (NEAs). That population is defined to have perihelia smaller than 1.3 AU.

Traditionally, NEAs are divided into four dynamical subpopulations—Amors, Apollos, Atens, and Atiras—whose orbits are categorized relative to Earth's orbit. Amors follow orbits that are always farther from the Sun than is Earth's. Atiras, by contrast, follow orbits that are always closer to the Sun than is Earth's. Apollos and Atens are both on Earth-crossing orbits. Based on a rare, dynamical subset of orbits found in our simulations of the NEA subpopulations, in 2012 I and my colleagues Brett Gladman and Henry Ngo, then all at the University of British Columbia, proposed the addition of a fifth subpopulation we called the Vatiras.[3] That asteroid class is similar in nature to Atiras, but they follow orbits that keep them closer to the Sun than Venus's orbit—hence their name as a play on Venus and Atira. Figure 2a shows a schematic of sample orbits for each of those five subpopulations.

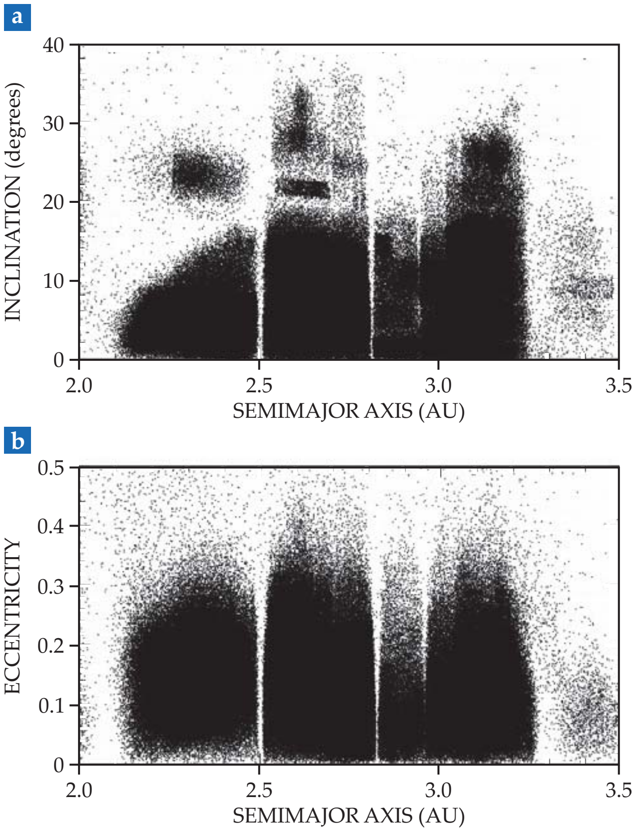

FIGURE 1. ORBITAL DISTRIBUTIONS of the roughly 525 000 asteroids in the main asteroid belt. The data come from the Minor Planet Center Orbit Database, a public list of computed orbits for all known small bodies in the solar system. The semimajor axis measures the average orbital distance from the Sun relative to the Earth–Sun distance (1 AU). **(a)** Inclination measures the angular tilt of the orbit out of the planetary plane. **(b)** Eccentricity measures the orbital ellipticity. Main-belt asteroids sit between the orbits of Mars and Jupiter on moderately elliptical and inclined orbits. So-called Kirkwood gaps can be seen at specific semimajor axes, where orbital resonances exist and the number of asteroids drops sharply. (Image by Sarah Greenstreet.)

Our NEA dynamical model and an updated model produced by the University of Helsinki's Mikael Granvik and colleagues in 2016 independently predict that the Amor, Apollo, Aten, Atira, and Vatira subpopulations contain roughly 39%, 55%, 4%, 1%, and less than 1% of NEAs, respectively, at any given time.[3,4] Together, the Amors and Apollos make up the vast majority (94%) of NEAs. That's partly the result of the much larger volume of near-Earth space they cover. The curves shown in figure 2b mark the boundaries of each subpopulation and follow the perihelia and aphelia of Earth, Venus, and Mercury. For example, while all NEAs must have perihelia that are less than 1.3 AU, Amors must have perihelia that are larger than Earth's aphelion (1.017 AU) to remain farther from the Sun than Earth's orbit is.

Apollos have perihelia that are smaller than Earth's aphelion and semimajor axes that are greater than the semimajor axis of Earth (1 AU). Atens have semimajor axes that are less than 1 AU and aphelia that are larger than Earth's perihelion (0.983 AU).

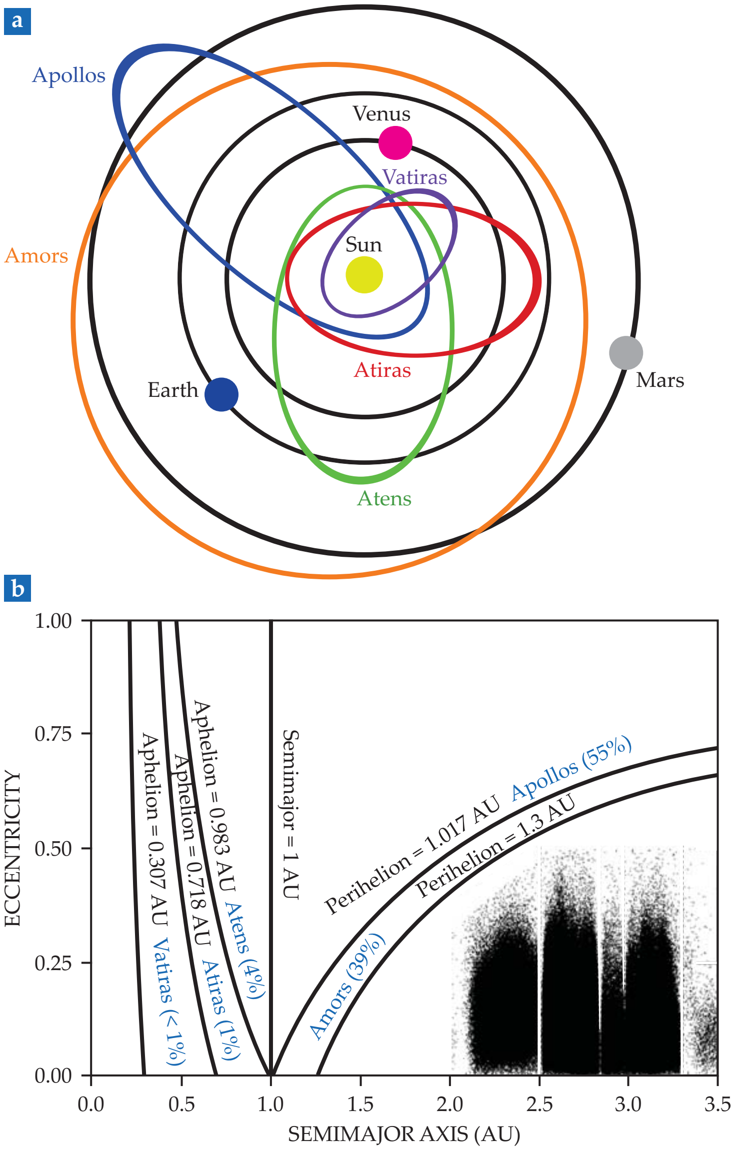

FIGURE 2. SCHEMATIC ORBITS of near-Earth-asteroid classes. **(a)** Those of Apollos and Atens cross Earth's orbit. Amors orbit the Sun entirely outside Earth's orbit, and Atiras orbit the Sun completely inside Earth's orbit. Vatiras are on orbits entirely inside Venus's orbit. **(b)** This projection shows the inner solar system in a plot of near-Earth asteroid eccentricities versus their semimajor axes. At the lower right are the known main-belt asteroids. The vast majority (Apollos and Amors) in the inner solar system reside outside Earth's semimajor axis (1 AU). The fraction of near-Earth asteroids in each subpopulation and the limits on their aphelia or perihelia are shown by their names. (Image by Sarah Greenstreet.)

Their orbital parameters make Apollos and Atens Earth-crossing. Atiras must have aphelia that are smaller than Earth's perihelion to stay closer to the Sun than Earth's orbit is at all times. Lastly, Vatiras have aphelia that are inside Venus's perihelion (0.718 AU) and outside Mercury's perihelion (0.307 AU). Any asteroids with aphelia inside Mercury's perihelion would remain closer to the Sun than Mercury's orbit is. Another reason Amors and Apollos are the most numerous NEAs is because they overlap the resonances where asteroids enter the NEA population. That overlap greatly enhances their number over the Atens, Atiras, and Vatiras, which lie much closer to the Sun than those resonances.

Generally, asteroids can reach the Aten, Atira, and Vatira subpopulations only through a series of planetary close encounters that cause their semimajor axes to jump to increasingly smaller values. The close encounters are more frequent in the inner solar system because of higher orbital speeds. But for the encounters to push asteroids into the three innermost NEA populations, they must occur in such a way that they cumulatively decrease, not increase, an asteroid's semimajor axis. As you can imagine, that process becomes increasingly difficult as asteroids reach smaller orbits and encounter fewer planets. Thus a large drop-off in asteroid population occurs between the Apollos and the Atens.

Likewise, it becomes more difficult to gravitationally scatter asteroids onto orbits decoupled from the planets—that is, orbits that are no longer planet-crossing—at the increasingly smaller orbits entirely interior to the orbits of Earth and Venus. For those reasons, Atiras are rare and Vatiras even rarer among the NEAs. And although it is theoretically possible, asteroids almost never reach orbits completely interior to Mercury's orbit.

Dynamical behavior

Despite the rarity of Atiras and Vatiras, they provide a unique glimpse into the dynamic environment of the innermost regions of our solar system. Any given asteroid that becomes a Vatira will have passed through the Amor, Apollo, Aten, and Atira populations to reach its eventual small orbit. Each Atira and Vatira will have taken a unique path from the main belt, often over tens of millions of years, and will have spent varying amounts of time in each population along the way.

Asteroids do not remain in the Atira and Vatira populations for long. Detailed dynamical simulations of Atira asteroids performed by Anderson Ribeiro of the Geraldo Di Biase University Center in Brazil and his colleagues indicate that the very planetary close encounters required to enter those hard-to-reach orbits are responsible for continually scattering the asteroids into and out of the Vatira and Atira populations many times during their lifetimes.[5] Those events keep the asteroids from lingering in either of the planet-decoupled populations.

As Gladman, Ngo, and I discovered in our simulations,[3] the asteroids typically spend only a couple million years—integrated over their lifetimes—as Atiras and a few hundred thousand years as Vatiras. It is possible for asteroids to enter the Vatira region and to remain there for more than a million years before leaving. However, such long-lived Vatiras are extremely rare. If most of those asteroids don't remain in the Atira and Vatira populations, where do they go? The frequent planetary close encounters generally push the asteroids outward, over tens of millions of years, back onto Venus- and Earth-crossing orbits. (The asteroids become Atens and Apollos.) Because the vast majority of Atiras and Vatiras do not remain

FIGURE 3. THE ZWICKY TRANSIENT FACILITY is located at the Palomar Observatory's 48-inch Samuel Oschin Telescope. The facility's twilight observing program is responsible for finding the three near-Earth asteroids with the shortest orbital periods known to date. (Image courtesy of Palomar/Caltech.)

decoupled from Earth and Venus, most eventually collide with one of those planets or with Mercury. Any that remain are frequently pushed onto Sun-grazing orbits, and some are even scattered back out to Mars-crossing orbits and potentially beyond the asteroid belt.

Dynamical simulations reveal the orbits in which Atiras and Vatiras spend most of their time and thus where it is best to look in the night sky to find them. Their rarity has made them of particular interest to telescopic surveys focused on asteroid discovery. Many of those surveys have dedicated time to searching for asteroids near the Sun, and some telescopes, such as the space-based *Near-Earth Object Surveillance Satellite* (*NEOSSat*),[6] were specifically designed to discover new Atens, Atiras, and Vatiras.

Not only are Atiras and Vatiras a rare part of the NEA population because of their difficulty in gravitationally scattering to small, planet-decoupled orbits, they are also challenging objects to observe in the night sky because of their close proximity to the Sun. The asteroids are never farther from the Sun than is Earth, so ground-based telescopes—which make most asteroid discoveries—must aim near the horizon during a brief period of time shortly after sunset and shortly before dawn to have any hope of capturing one in an image. Considering that observational limit, when new discoveries of such asteroids are made, it is quite exciting.

Atira discoveries

To date, 23 known asteroids orbit the Sun in the Atira population. They range in size from 50 m to 5 km. Both the Granvik and Greenstreet models estimate the existence of 10 Atiras[3,4] with diameters larger than a kilometer. Beyond the six known Atiras in that size range, few large ones are likely left to be discovered. The number of Atiras with increasingly smaller diameters is much greater, so many more remain to be found.

The first confirmed Atira asteroid was discovered in 2003 by the Lincoln Near-Earth Asteroid Research program at the MIT Lincoln Laboratory near Socorro, New Mexico. Called 163693 Atira, it was named after the Pawnee goddess of Earth. The asteroid follows a highly inclined orbit with an aphelion just inside Earth's perihelion—the cutoff for orbits interior to Earth's. Because the asteroid's aphelion is so close to Earth's perihelion, it is possible for the Atira to have close encounters with Earth. In January 2017 one such encounter occurred when the asteroid passed close enough for the Arecibo Observatory to capture it in a series of radar images.

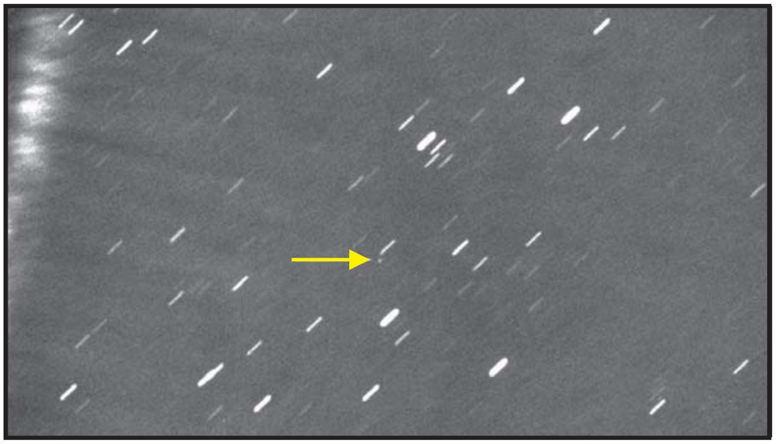

FIGURE 4. A VATIRA ON FILM. The Virtual Telescope Project took this image on 8 January 2020. It shows the average of 14 60-second exposures. They were combined to track the motion of 2020 AV2—the white dot, marked by an arrow—across the sky to reveal the asteroid as a point source, against which the stars streak. (Image courtesy of Gianluca Masi, Virtual Telescope Project.)

Radar astronomy uses reflected microwaves from nearby solid targets to constrain the shape, size, and spin state of an asteroid. As reported by Edgard Rivera-Valentín and colleagues, all at Arecibo Observatory at the time, the radar measurements revealed an unexpected finding—that 163693 Atira is a binary system.[7] It consists of two objects, a primary and a smaller secondary, that orbit each other. The diameter of the primary was measured at 4.8 ± 0.5 km with an elongated and very angular shape; the diameter of the secondary was 1.0 ± 0.3 km. The semimajor axis of the binary was fit at near 6 km with an orbital period of roughly 16 hours.

Astronomers are not lucky enough to get radar measurements of many asteroids, but telescopic observations reveal many of their features. The asteroids' brightness, distance, and reflectivity reveal their size. The periodicity at which that brightness changes reveals their rotation periods. And spectral analysis reveals their surface composition. Using dynamical simulations of an observed orbit, astronomers can learn where an asteroid likely came from, how long it is likely to stay on its current orbit, and what its most likely future trajectory will be. Using our dynamical model of the NEA orbital distribution,[3] we can say that 163693 Atira probably entered the NEA population through the inner portion of the main asteroid belt and likely took tens of millions of years to scatter down to its current region. It will probably scatter into and out of the Atira population several times with an integrated lifetime in the Atira region of a couple million years before most likely colliding with a terrestrial planet.

Over time, more Atira-class asteroids have been discovered that have increasingly smaller orbits. In 2019 astronomers found two Atiras that have the smallest semimajor axes known and aphelia that put them near the Atira–Vatira boundary (Venus's perihelion). The first, 2019 AQ3, was discovered on 4 January by the twilight observing program at the Zwicky Transient Facility[8] at Palomar Observatory, shown in figure 3. The second, 2019 LF6, was discovered five months later, on 10 June.

The first Vatira

Within a year of the discoveries of 2019 AQ3 and 2019 LF6, the first Vatira-class asteroid was spotted by the same program at the Zwicky Transient Facility that had discovered the two Atiras. Figure 4 shows the asteroid appearing as a tiny dot in the night sky four days after its discovery. Designated 2020 AV2, the asteroid has an aphelion well inside the Venus perihelion cut-off, which makes its orbit entirely inside Venus's orbit. As estimated by Marcel Popescu of the Astronomical Institute of the Romanian Academy and colleagues, 2020 AV2 is roughly 1.5 km in diameter.[9] And to judge by the Greenstreet and Granvik dynamical models,[3,4] it is likely one of two Vatiras of that size currently in existence.

Popescu and colleagues classified the composition of 2020 AV2 as one that dominates the inner main belt.[9] The composition is consistent with our model prediction that the asteroid most likely originated at the inner edge of the main belt before making the long journey to the Vatira population.[3,10] It will likely remain a Vatira for a few hundred thousand years before scattering back out through a Venus-crossing Atira orbit to the Earth-crossing region, where it will most likely collide with Venus or Earth several million years from now.[10] The current orbit of 2020 AV2 puts it very close to the 3:2 resonance with Venus.[10,11] Unlike the resonances located in the main-belt Kirkwood gaps, that resonance with Venus is relatively stable, given the scarcity of resonances in the innermost portion of the solar system. Vatiras can remain in the resonance for millions of years, making the Venus resonance a likely place where other Vatiras are lurking and thus a good hunting ground for discovering more asteroids in that class.

Asteroid surveys, such as the twilight observing program at the Zwicky Transient Facility and the space-based *NEOSSat*, are ongoing. In addition, two large observing programs—the Vera C. Rubin Observatory's Legacy Survey of Space and Time and NASA's Near-Earth Object Surveillance Mission—are upcoming. Those new programs are likely to vastly increase the number of known NEAs, particularly given the new software being developed to prepare for the deluge of data from the new surveys. For example, using a program[12] built by the University of Washington's Dirac Institute, the cloud-based Asteroid Decision Analysis and Mapping platform will allow the B612 Asteroid Institute to extract even the trickiest-to-find asteroids among the data.

REFERENCES

1. D. Kirkwood, *Meteoric Astronomy: A Treatise on Shooting-Stars, Fire Balls, and Aerolites*, J. B. Lippincott (1867).
2. P. Farinella et al., *Nature* **371**, 314 (1994).
3. S. Greenstreet, H. Ngo, B. Gladman, *Icarus* **217**, 355 (2012).
4. M. Granvik et al., *Icarus* **312**, 181 (2018).
5. A. O. Ribeiro et al., *Mon. Not. R. Astron. Soc.* **458**, 4471 (2016).
6. A. R. Hildebrand et al., *Earth, Moon, Planets* **95**, 33 (2004).
7. E. G. Rivera-Valentín et al., *Cent. Bur. Electron. Teleg.* **4347**, 1 (2017).
8. Q. Ye et al., *Astron. J.* **159**, 70 (2020).
9. M. Popescu et al., *Mon. Not. R. Astron. Soc.* **496**, 3572 (2020).
10. S. Greenstreet, *Mon. Not. R. Astron. Soc. Lett.* **493**, L129 (2020).
11. C. de la Fuente Marcos, R. de la Fuente Marcos, *Mon. Not. R. Astron. Soc. Lett.* **494**, L6 (2020).
12. J. Moeyens et al., http://arxiv.org/abs/2105.01056.