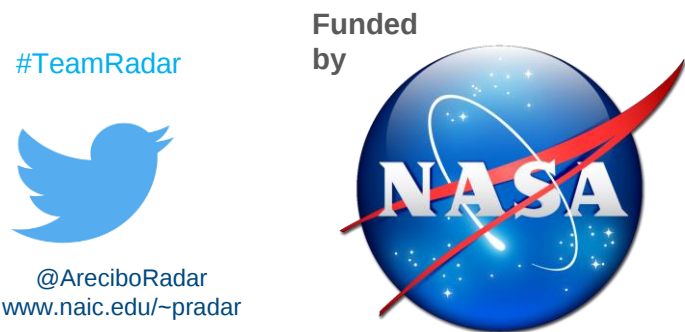


The Potentially Hazardous Binary and Triple Near-Earth Asteroids Observed with the Arecibo Planetary Radar System

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The legacy Arecibo Planetary Radar System:

- S-band (12.6 cm, 2380 MHz)
- 1 MW transmitter (two 500 MW klystrons)
- Range resolution as fine as 7.5 m
- Radial velocity resolution as fine as 1 mm/s

A polarized wave with well-known characteristics is transmitted, the echo from the target is received in two polarizations, and compared to the transmitted signal. Any change is due to the target properties.

Radar can measure distance with precision of meters, and speed with precision of mm/s.

How can radar support planetary defense?

- Small body astrometry: radar can refine orbits with great precision, allowing to quickly decrease orbit uncertainty and extend the predictability window.
- Detect orbit perturbation, helping to know more precisely the object's trajectory in the future (e.g., the thermal radiation driven Yarkovsky effect).
- Characterization: shape, spin, and identify satellites (binary and triple systems). Radar can also reveal surface properties
- Mission support (e.g. DART mission)

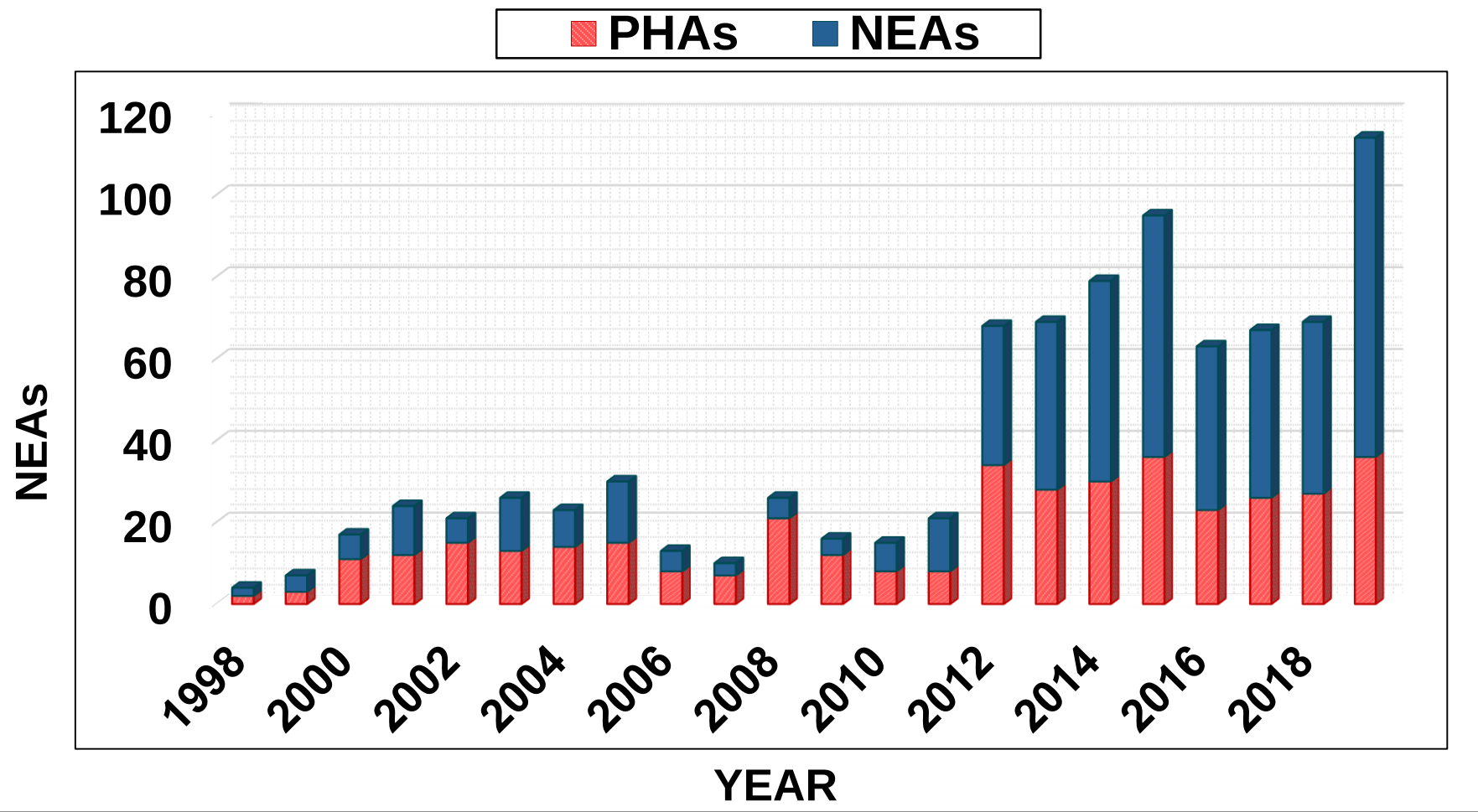


Fig. 1: Detection history of Near-Earth asteroid (NEA) at Arecibo.

Table 2: Dynamical properties of the Binary and triple PHAs observed at Arecibo. The periods were extracted from the <https://ssd.jpl.nasa.gov/>.

ASTEROID	Orbit type	MOID (AU)	Close ap. <0.05 (AU)	P (hours)	Close ap. Date	a(AU)	e	i(deg)	H (mag)	Q(AU)	q(AU)	Radar obs. YY	Binary/Triple	Equal mass
2020BX12	Apollo	0.001295	0.0445	2.8	2101-Jan-31	1.599	0.527	40.1	20.6	2.442	0.757	2020	Binary	
164121 2003YT1	Apollo	0.003093	0.01133	2.343	2073-Apr-29	1.11	0.292	44.1	16.2	1.434	0.785	2004	Binary	
143649 2003QQ47	Apollo	0.003799	NA	2.6446	NA	1.085	0.187	62.1	17.4	1.288	0.882	2021	Binary	
69230 Hermes	Apollo	0.004403	0.0282	13.894	2040-Apr-25	1.654	0.624	6.1	17.5	2.686	0.622	2003	Binary	Yes
2003SS84	Apollo	0.005106	0.04602	NA	2054-Oct-04	1.932	0.572	5.5	21.7	3.037	0.827	2003	Binary	
461852 2006GY2	Apollo	0.007576	0.43341	2.25	2039-Apr-21	1.853	0.494	30.6	18.7	2.768	0.938	2006	Binary	
399774 2005NB7	Apollo	0.008368	0.47649	3.4882	2043-May-29	2.042	0.516	12.7	18.7	3.096	0.988	2008	Binary	
311066 2004DC	Apollo	0.008874	0.1901	2.5709	2029-May-13	1.634	0.4	19.4	18	2.288	0.981	2006	Binary	
162000 1990OS	Apollo	0.008999	0.02038	2.536	2053-Nov-16	1.68	0.463	1.1	20	2.458	0.902	2003	Binary	
357439 2004BL86	Apollo	0.009430	0.02388	2.6205	2096-Jan-25	1.502	0.403	23.7	19	2.107	0.896	2015	Binary	
494658 2000UG11	Apollo	0.010184	0.01994	4.44	2142-Nov-12	1.934	0.573	8.9	20.4	3.042	0.826	2000	Binary	
374851 2006VV2	Apollo	0.010223	0.36507	2.425	2055-Apr-20	2.388	0.602	23.6	16.6	3.826	0.949	2007	Binary	
363027 1998ST27	Aten	0.010293	0.0238	3	2024-Oct-12	0.819	0.53	21	19.4	1.253	0.385	2001	Binary	
2018EB	Apollo	0.010421	0.03364	3.16	2059-Apr-04	1.017	0.012	29.4	21.7	1.029	1.005	2018	Binary	
450894 2008BT18	Apollo	0.011056	0.18701	2.5702	2051-Jul-31	2.222	0.598	8.1	18.2	3.551	0.894	2008	Binary	
66391 1999KW4	Aten	0.013376	0.01553	2.7645	2036-May-25	0.642	0.688	38.9	16.3	1.084	0.2	2001	Binary	
185851 2000DP107	Apollo	0.015048	0.04239	2.7754	2067-Sep-20	1.365	0.377	8.7	18.2	1.88	0.85	2000	Binary	
226514 2003UX34	Apollo	0.015114	0.04355	NA	2149-Jan-05	1.095	0.616	2.6	20	1.77	0.421	2017	Binary	
136617 1994CC	Apollo	0.015924	0.01702	2.3886	2074-Jun-11	1.638	0.417	4.7	17.7	2.321	0.955	2009	Triple	
2005YQ96	Aten	0.017767	0.03731	NA	2040-Jan-03	0.744	0.333	22.2	20.4	0.992	0.496	2014	Binary	
385186 1994AW1	Amor	0.019498	NA	2.5193	NA	1.105	0.075	24.1	17.5	1.188	1.105	2015	Binary	
488453 1994XD	Apollo	0.020118	0.02114	2.7365	2023-Jun-12	2.356	0.73	4.3	19.1	4.076	0.637	2005	Binary	
363599 2004FG11	Apollo	0.020554	0.01815	7.021	2134-Nov-25	1.589	0.724	3.1	20.9	2.739	0.438	2012	Binary	
2017YE5	Apollo	0.021511	NA	20.6	NA	2.82	0.71	6.2	19.3	4.822	0.817	2018	Binary	Yes
85938 1999DJ4	Apollo	0.021758	NA	2.5141	NA	1.851	0.483	9.2	18.4	2.745	0.957	2004	Binary	
363067 2000CO101	Apollo	0.022657	0.02522	5.12	2057-Sep-16	1.075	0.09	15.3	19	1.172	0.979	2009	Binary	
1862 Apollo	Apollo	0.025812	0.03529	3.065	2046-Nov-13	1.471	0.56	6.4	16.3	2.295	0.647	2005	Binary	
35107 1991VH	Apollo	0.025992	0.0445	2.6236	2065-Aug-06	1.136	0.144	13.9	16.7	1.3	0.973	2008	Binary	
2014WZ120	Apollo	0.027745	0.04919	3.361	2149-Nov-28	2.354	0.571	20.9	20.4	3.62	0.8	2014	Binary	
175706 1996FG3	Apollo	0.028302	0.03076	3.5942	2166-Nov-27	1.054	0.35	2	18	1.423	0.685	2011	Binary	
2016AZ8	Apollo	0.029003	0.03286	16.897	2151-Jan-10	1.32	0.355	5.6	21	1.79	0.852	2019	Binary	
2002KK8	Amor	0.029796	NA	NA	NA	1.967	0.469	24.6	20.5	2.889	1.045	2002	Binary	
2002BM26	Apollo	0.031361	NA	2.7	NA	1.832	0.444	16.2	19.8	2.645	1.019	2002	Binary	
153958 2002AM31	Apollo	0.031671	0.03406	2.8174	2032-Jul-29	1.705	0.452	4.6	18.2	2.475	0.935	2012	Binary	
1994CJ1	Apollo	0.031783	NA	30	NA	1.489	0.325	2.3	21.3	1.973	1.005	2014	Binary	Yes
285263 1998QE2	Amor	0.032949	0.49027	4.749	2028-Jul-12	2.421	0.571	12.9	17.1	3.805	1.039	2013	Binary	
2013WT44	Apollo	0.036429	0.02033	2.8849	2133-Mar-23	2.259	0.568	12.2	19.6	3.542	0.975	2014	Binary	
65803 Didymos	Apollo	0.040448	0.04965	2.2593	2062-Oct-20	1.642	0.383	3.4	17.9	2.275	1.013	2003	Binary	
3122 Florence	Amor	0.043366	0.04996	2.3581	2057-Sep-02	1.768	0.423	22.2	14.1	2.516	1.02	2017	Triple	
481532 2007LE	Apollo	0.045633	NA	2.603	NA	1.839	0.517	29.5	19.2	2.79	0.889	2012	Binary	
348400 2005JF21	Amor	0.046433	NA	2.4149	NA	2.224	0.535	10.9	17.1	3.415	1.034	2015	Triple	
138095 2000DK79	Amor	0.049978	0.04775	4.243	2103-Nov-07	1.777	0.414	60.7	15.8	2.513	1.04	2013	Binary	

Highlighted in magenta are the binary systems that have the highest resolution radar images, which are more suitable for 3D shape model. In red are the PHAs that are triple systems; MOID is the Earth minimum orbital intersection distance

Radar detection of an asteroid satellite in radar images can provide information such as the separation distance between two components and mutual orbital period, and also makes it possible to estimate the mass of the system and density. This information is valuable to support our understanding of asteroid formation and evolution, as well as planning for small bodies space missions.

Potentially hazardous asteroids (PHAs) are near-Earth asteroids (NEAs) that are larger than 140 meters and that can come closer to Earth than 0.05 au (~20 Lunar Distances). To date, over 31,000 NEAs were discovered, and more than 2300 PHAs are known.

The population of binary and triple NEAs observed with the Arecibo's S-band planetary radar system includes: **58 objects, 7% of a total of 867 NEAs observed. Among the NEAs, 345 are classified as PHAs, 42 of them are binary/triple systems, which is about 12% of the PHAs observed at Arecibo.**

Table 1: Binary/triple near-Earth asteroids observed with Arecibo's planetary radar system.

Binary/Triple	58
Binary	54
Triple	4
Equal mass binary	4
PHA	42

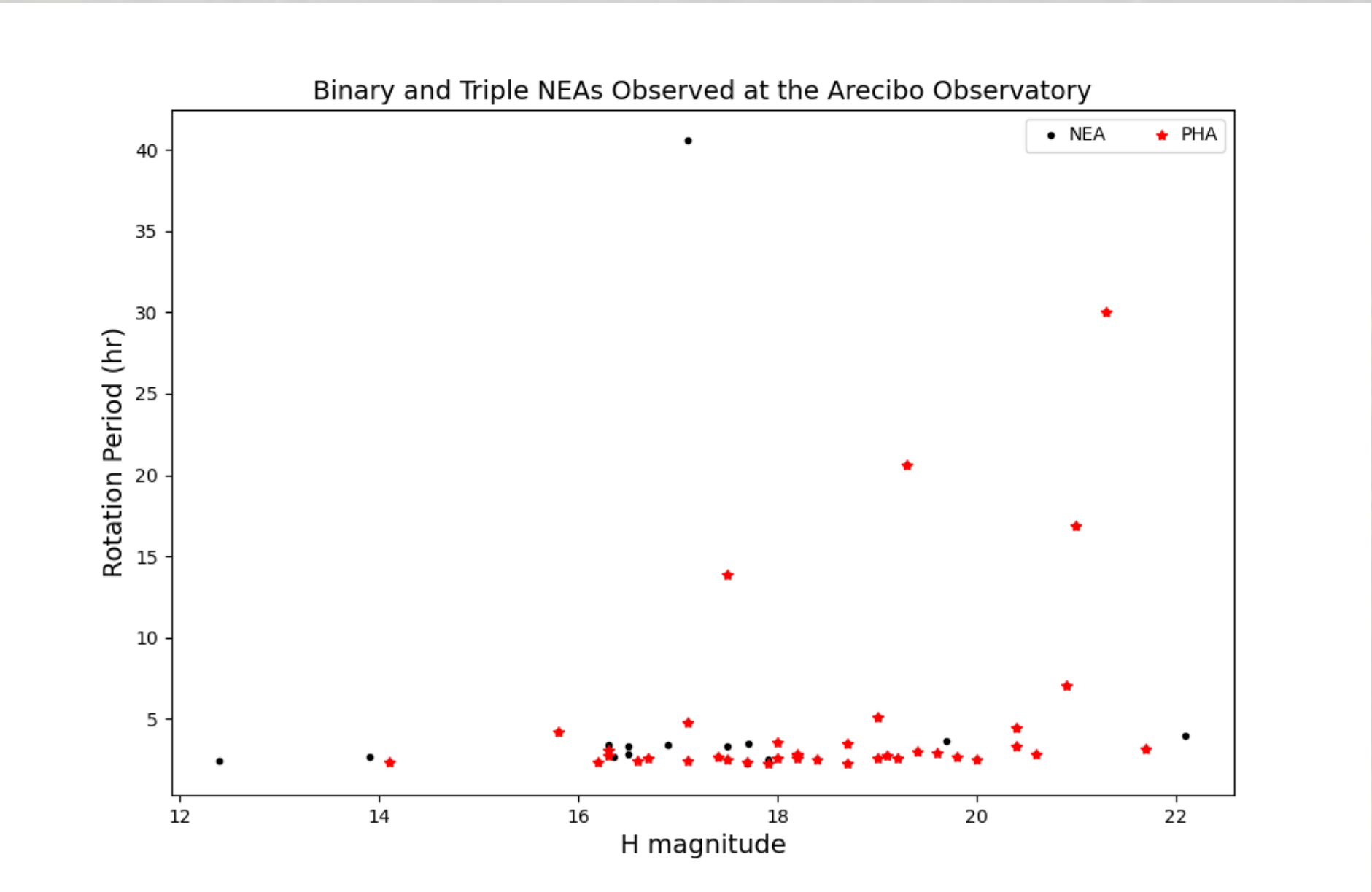


Fig. 2: Rotation period and H for binary/triple NEAs observed at Arecibo

