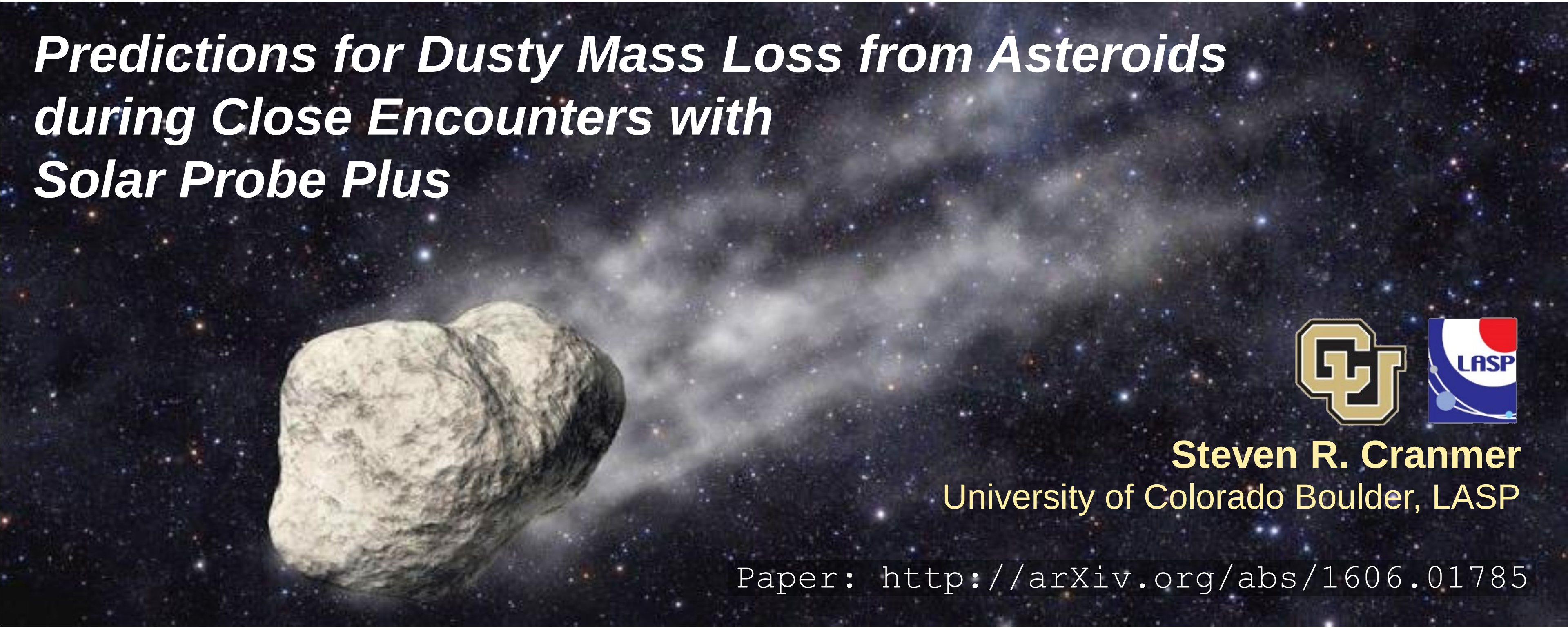

Predictions for Dusty Mass Loss from Asteroids during Close Encounters with Solar Probe Plus

Steven R. Cranmer
University of Colorado Boulder, LASP

`Paper: http://arXiv.org/abs/1606.01785`

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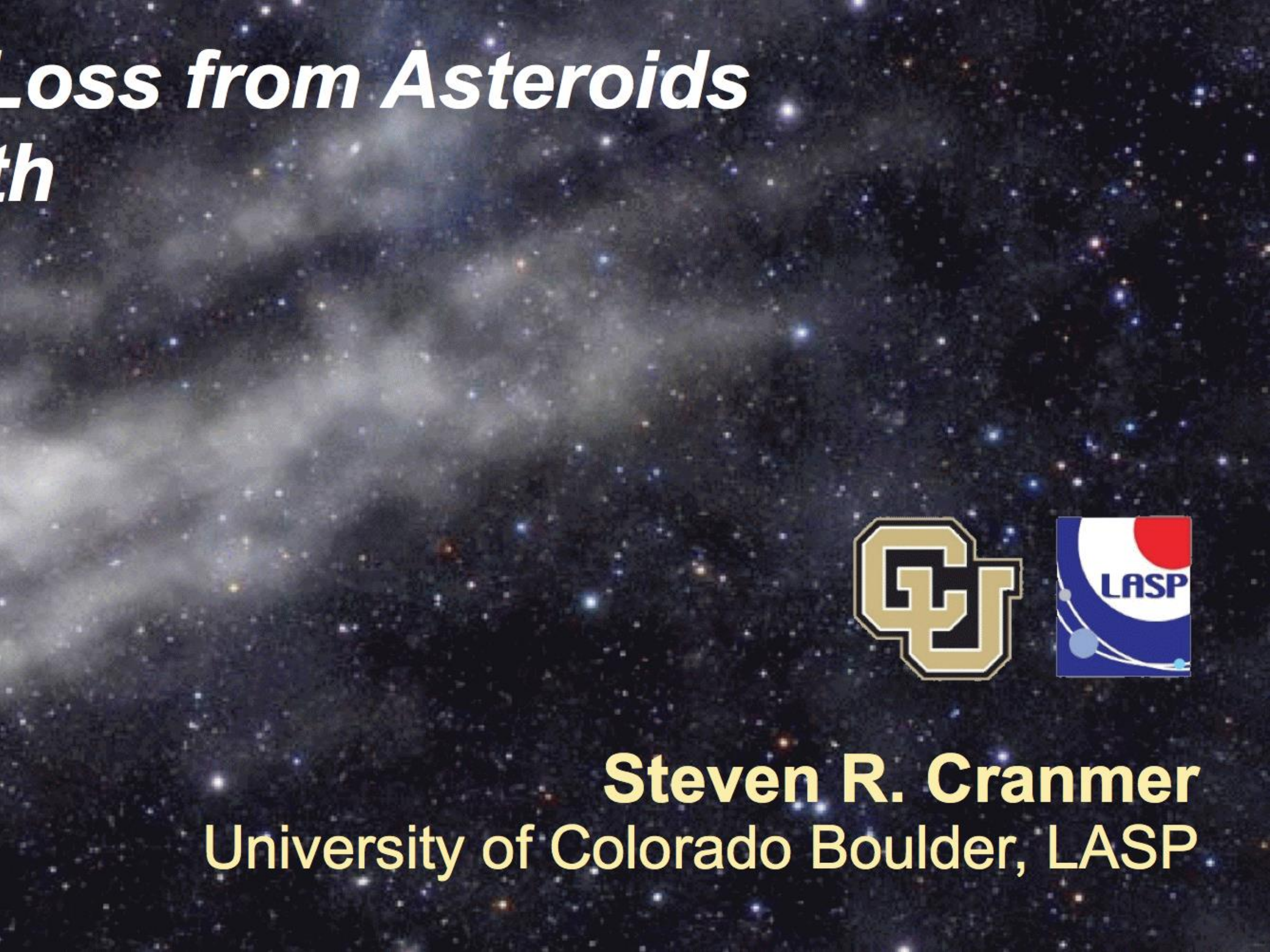


Loss from Asteroids th

Steven R. Cranmer

University of Colorado Boulder, LASP

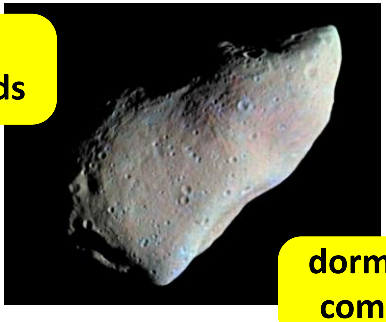
Introduction

- The goal of this work is to call the community's attention to the likelihood that the **Solar Probe Plus (SPP)** spacecraft will be well-positioned to observe mass loss from Mercury-crossing asteroids in the inner heliosphere.

- Specifically, we predict that there will be several times during the SPP mission when its WISPR instrument will be able to detect visible-light emission from the asteroids themselves and (in a few cases) from associated coma-like dust clouds that may subtend almost a degree of angular width on the sky.

- These observations could fill in a large gap between the properties of several previously distinct populations:

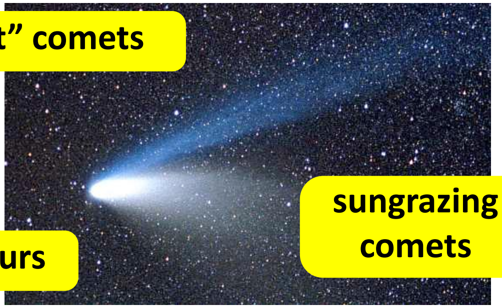
active asteroids



dormant comets

"main belt" comets

Centaurs

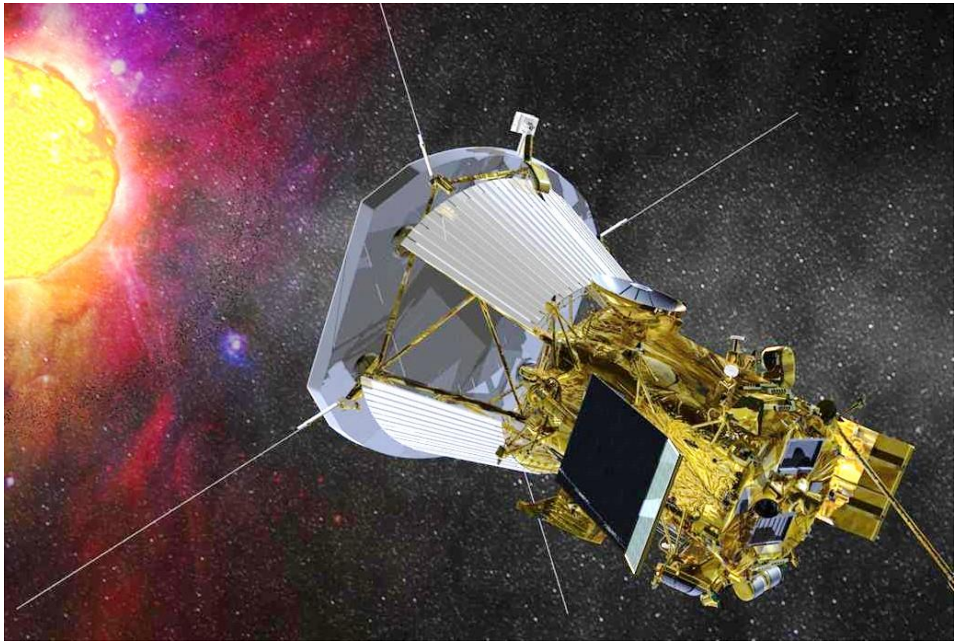


sungrazing comets

and help complete the census of primordial solar system material.

Solar Probe Plus

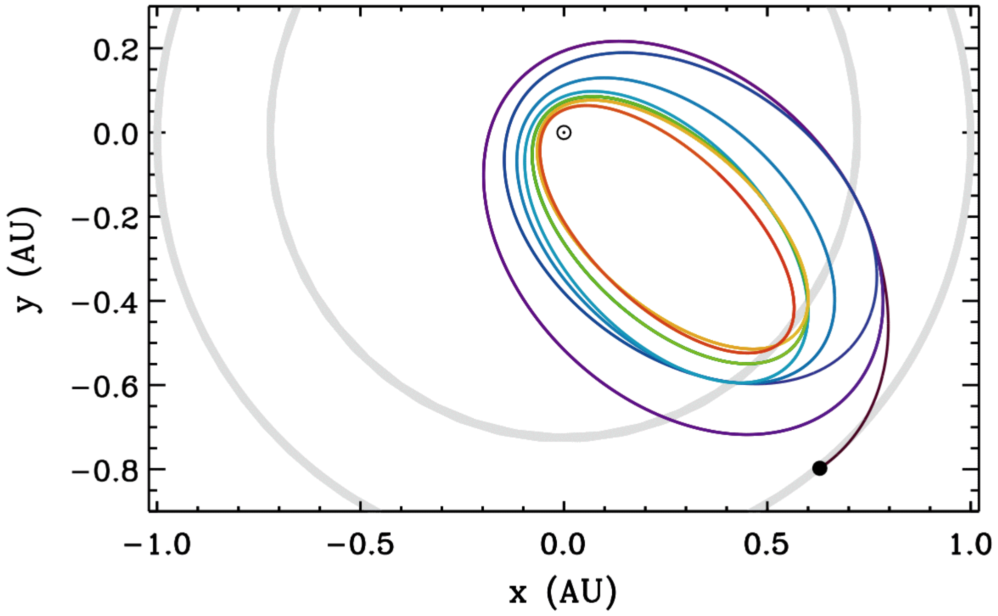
- Solar Probe Plus (SPP) will be the first spacecraft to fly into the Sun's corona (Fox et al. 2015).
- SPP's main science goal is to determine the structure & dynamics of the coronal magnetic field, understand how the solar corona & wind are heated & accelerated, and determine what processes accelerate energetic particles.

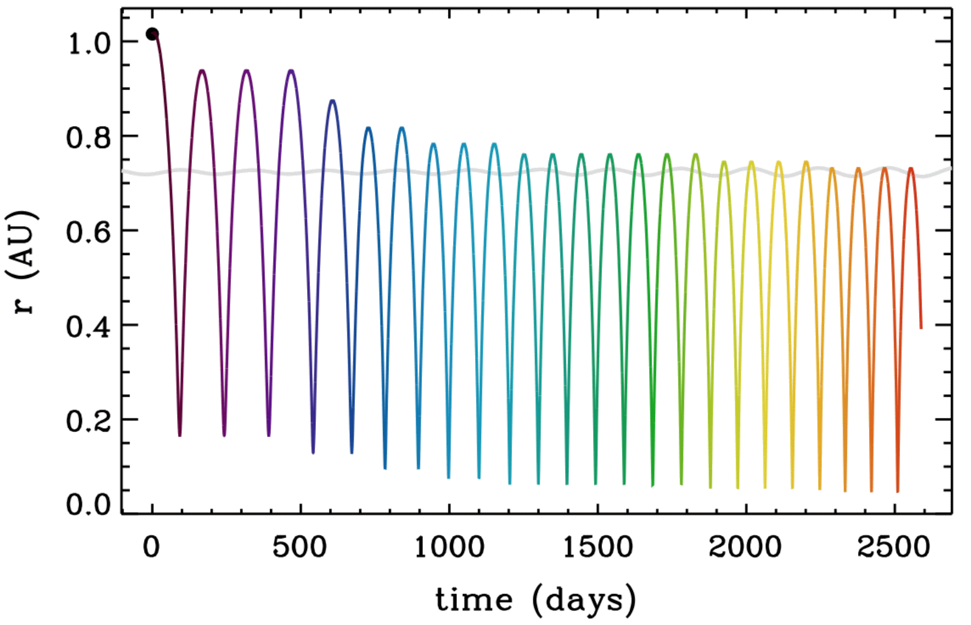


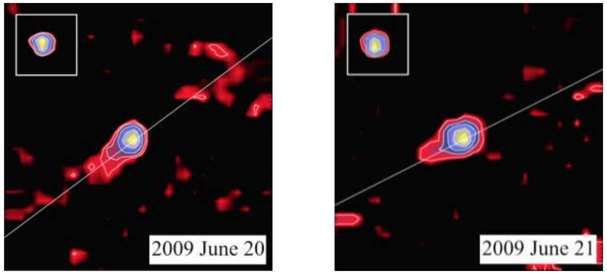
- In addition to a suite of *in situ* plasma & field instruments, the **Wide-field Imager for SPP** (WISPR, Vourlidas et al. 2015) will observe visible-light photons over large fields of view.
- The primary goal of WISPR is to observe K-corona emission from Thomson-scattered electrons and F-corona emission from dust, but it will also search for sungrazing comets and putative Vulcanoids (see, e.g., Steffl et al. 2013).

Solar Probe Plus

- Planned Launch: July 30, 2018.
- SPP will use multiple gravity-assist maneuvers with Venus to enter the inner heliosphere within the first year of the mission.
- Minimum perihelion distance: 0.0459 AU (9.8 solar radii!)
- WISPR is a follow-on of the SECCHI instrument suite from *STEREO*, which was used to detect comet-like tail emission from active asteroid 3200 Phaethon at its perihelion (Jewitt et al. 2013).



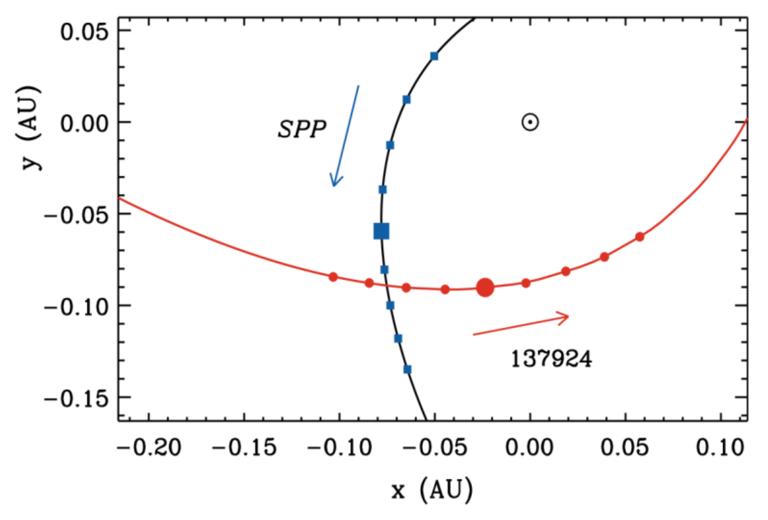




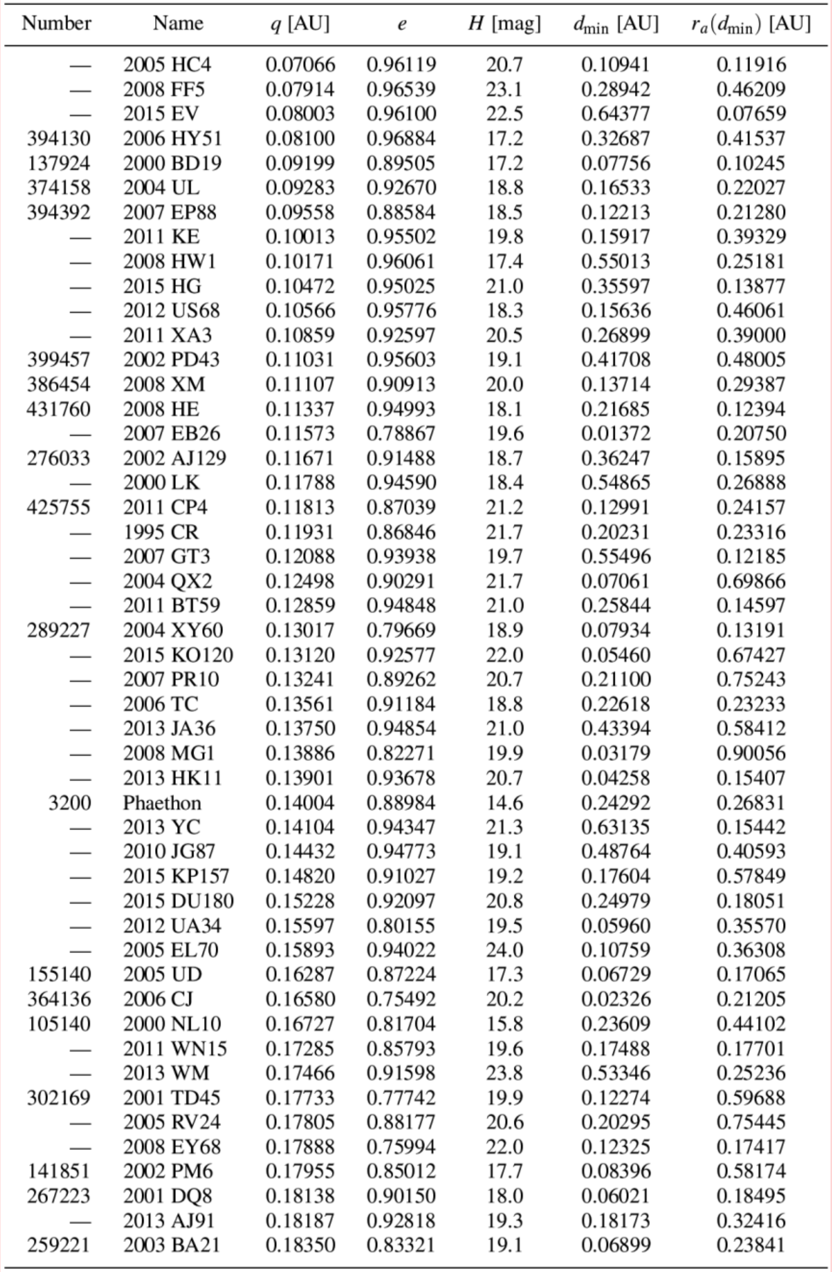
Asteroid selection

- As of late 2015, there are $\left\{\begin{array}{c}\mathbf{6}\\ \mathbf{63}\\ \mathbf{222}\end{array}\right\}$ known asteroids with perihelia $\left\{\begin{array}{l}\leq \mathbf{0.1\ AU}\\ \leq \mathbf{0.2\ AU}\\ \leq \mathbf{0.3\ AU}\end{array}\right.$
- To produce our final database of **97 asteroids,** we selected all 63 with $q \leq 0.2$ AU, and only those between 0.2 and 0.3 AU with visible magnitudes $H < 18$.
- Dimmer asteroids between 0.2 and 0.3 AU (and all others with $q > 0.3$ AU) were found to be unable to produce large dust coma/tail strucures.
- Asteroid ephemerides were obtained from NASA/JPL's Horizons database: http://ssd.jpl.nasa.gov/horizons.cgi
- SPP's planned trajectory was obtained from the SPP team (thanks to Kelly Korreck and Martha Kusterer).
- On next page, the list shows minimum distances (d_{min}) between each asteroid and SPP, and the asteroid heliocentric distance (r_a) at times of closest encounter.

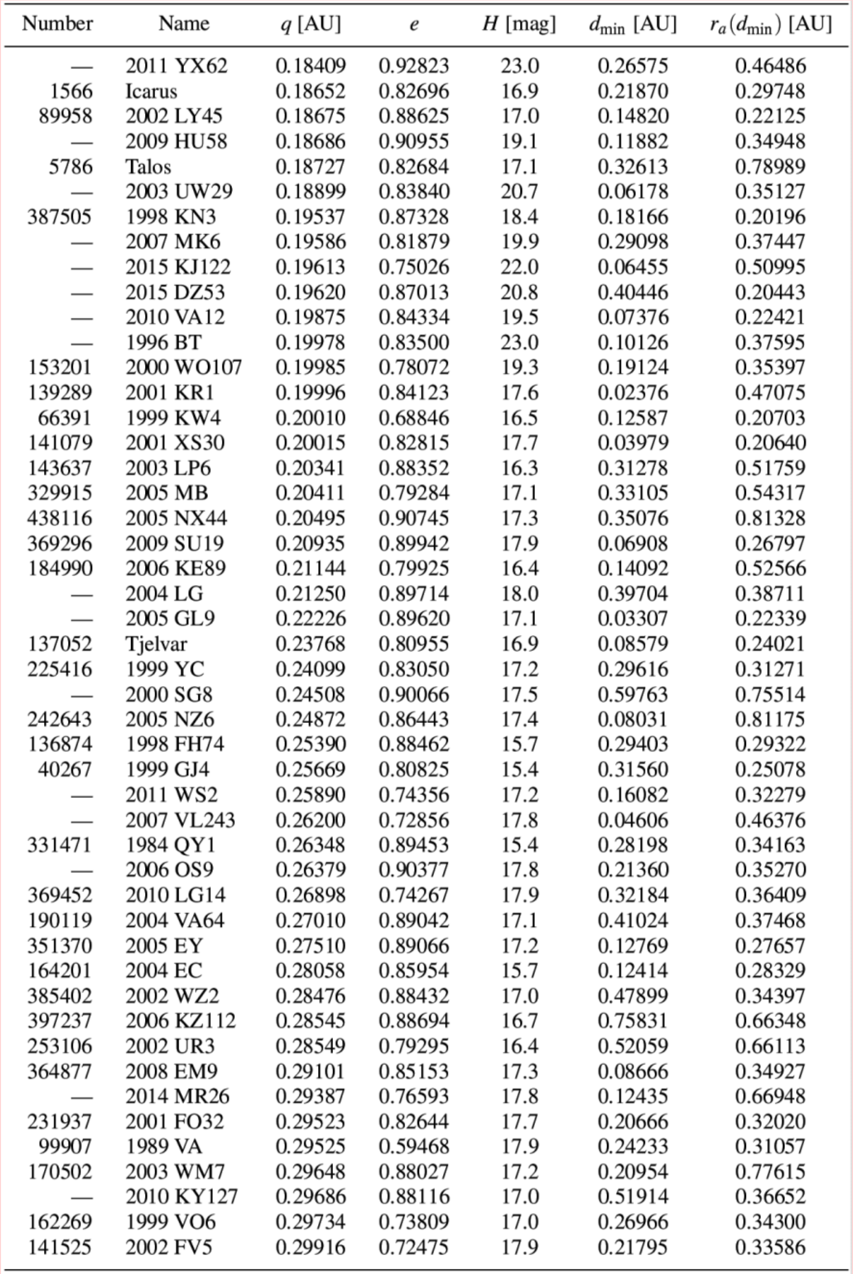
Example close encounter: Sept. 1, 2022



List of selected asteroids



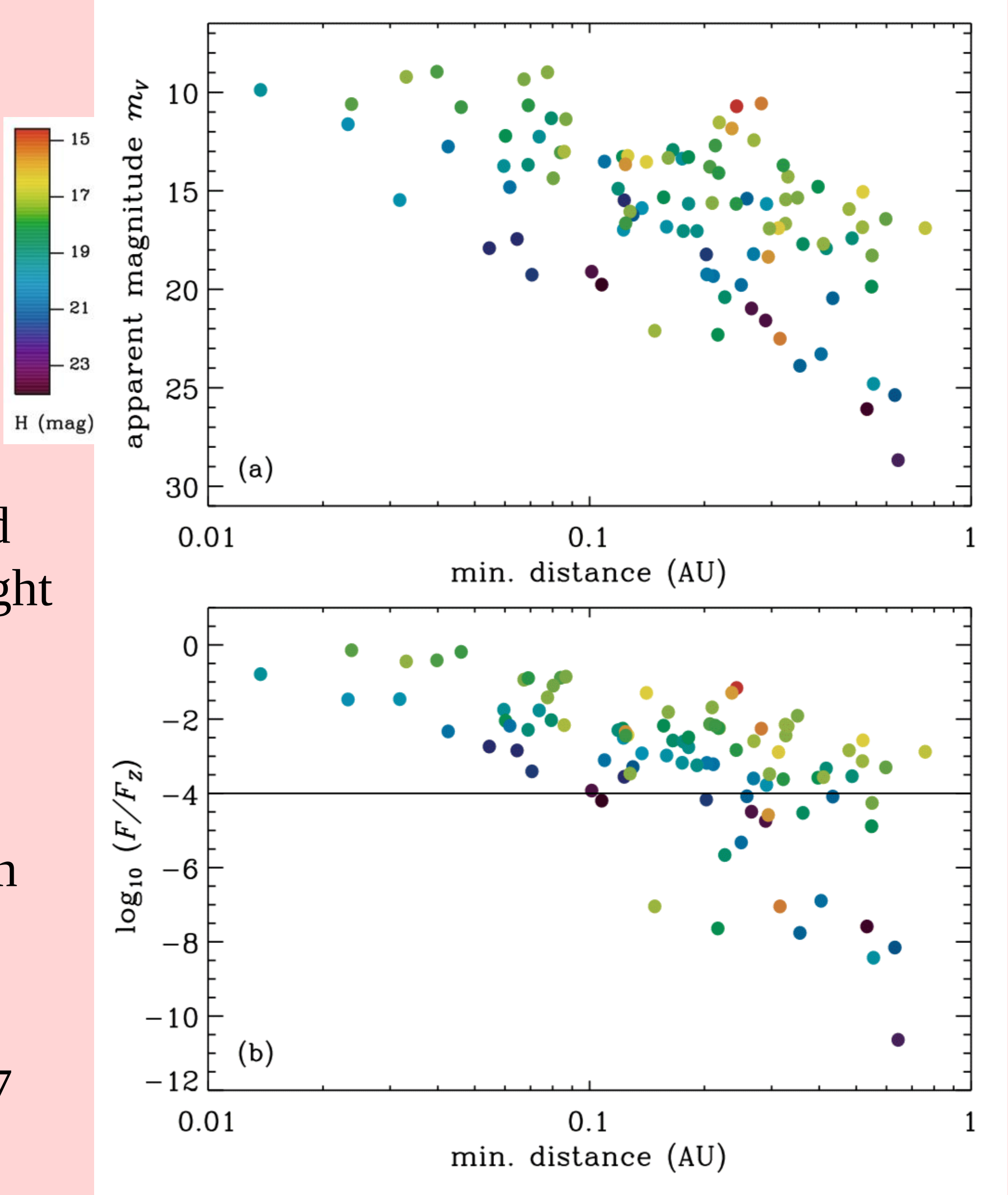
Number	Name	q [AU]	e	H [mag]	$d_{\min}$ [AU]	$r_a(d_{\min})$ [AU]
—	2005 HC4	0.07066	0.96119	20.7	0.10941	0.11916
—	2008 FF5	0.07914	0.96539	23.1	0.28942	0.46209
—	2015 EV	0.08003	0.96100	22.5	0.64377	0.07659
394130	2006 HY51	0.08100	0.96884	17.2	0.32687	0.41537
137924	2000 BD19	0.09199	0.89505	17.2	0.07756	0.10245
374158	2004 UL	0.09283	0.92670	18.8	0.16533	0.22027
394392	2007 EP88	0.09558	0.88584	18.5	0.12213	0.21280
—	2011 KE	0.10013	0.95502	19.8	0.15917	0.39329
—	2008 HW1	0.10171	0.96061	17.4	0.55013	0.25181
—	2015 HG	0.10472	0.95025	21.0	0.35597	0.13877
—	2012 US68	0.10566	0.95776	18.3	0.15636	0.46061
—	2011 XA3	0.10859	0.92597	20.5	0.26899	0.39000
399457	2002 PD43	0.11031	0.95603	19.1	0.41708	0.48005
386454	2008 XM	0.11107	0.90913	20.0	0.13714	0.29387
431760	2008 HE	0.11337	0.94993	18.1	0.21685	0.12394
—	2007 EB26	0.11573	0.78867	19.6	0.01372	0.20750
276033	2002 AJ129	0.11671	0.91488	18.7	0.36247	0.15895
—	2000 LK	0.11788	0.94590	18.4	0.54865	0.26888
425755	2011 CP4	0.11813	0.87039	21.2	0.12991	0.24157
—	1995 CR	0.11931	0.86846	21.7	0.20231	0.23316
—	2007 GT3	0.12088	0.93938	19.7	0.55496	0.12185
—	2004 QX2	0.12498	0.90291	21.7	0.07061	0.69866
—	2011 BT59	0.12859	0.94848	21.0	0.25844	0.14597
289227	2004 XY60	0.13017	0.79669	18.9	0.07934	0.13191
—	2015 KO120	0.13120	0.92577	22.0	0.05460	0.67427
—	2007 PR10	0.13241	0.89262	20.7	0.21100	0.75243
—	2006 TC	0.13561	0.91184	18.8	0.22618	0.23233
—	2013 JA36	0.13750	0.94854	21.0	0.43394	0.58412
—	2008 MG1	0.13886	0.82271	19.9	0.03179	0.90056
—	2013 HK11	0.13901	0.93678	20.7	0.04258	0.15407
3200	Phaethon	0.14004	0.88984	14.6	0.24292	0.26831
—	2013 YC	0.14104	0.94347	21.3	0.63135	0.15442
—	2010 JG87	0.14432	0.94773	19.1	0.48764	0.40593
—	2015 KP157	0.14820	0.91027	19.2	0.17604	0.57849
—	2015 DU180	0.15228	0.92097	20.8	0.24979	0.18051
—	2012 UA34	0.15597	0.80155	19.5	0.05960	0.35570
—	2005 EL70	0.15893	0.94022	24.0	0.10759	0.36308
155140	2005 UD	0.16287	0.87224	17.3	0.06729	0.17065
364136	2006 CJ	0.16580	0.75492	20.2	0.02326	0.21205
105140	2000 NL10	0.16727	0.81704	15.8	0.23609	0.44102
—	2011 WN15	0.17285	0.85793	19.6	0.17488	0.17701
—	2013 WM	0.17466	0.91598	23.8	0.53346	0.25236
302169	2001 TD45	0.17733	0.77742	19.9	0.12274	0.59688
—	2005 RV24	0.17805	0.88177	20.6	0.20295	0.75445
—	2008 EY68	0.17888	0.75994	22.0	0.12325	0.17417
141851	2002 PM6	0.17955	0.85012	17.7	0.08396	0.58174
267223	2001 DQ8	0.18138	0.90150	18.0	0.06021	0.18495
—	2013 AJ91	0.18187	0.92818	19.3	0.18173	0.32416
259221	2003 BA21	0.18350	0.83321	19.1	0.06899	0.23841



Number	Name	q [AU]	e	H [mag]	$d_{\min}$ [AU]	$r_a(d_{\min})$ [AU]
—	2011 YX62	0.18409	0.92823	23.0	0.26575	0.46486
1566	Icarus	0.18652	0.82696	16.9	0.21870	0.29748
89958	2002 LY45	0.18675	0.88625	17.0	0.14820	0.22125
—	2009 HU58	0.18686	0.90955	19.1	0.11882	0.34948
5786	Talos	0.18727	0.82684	17.1	0.32613	0.78989
—	2003 UW29	0.18899	0.83840	20.7	0.06178	0.35127
387505	1998 KN3	0.19537	0.87328	18.4	0.18166	0.20196
—	2007 MK6	0.19586	0.81879	19.9	0.29098	0.37447
—	2015 KJ122	0.19613	0.75026	22.0	0.06455	0.50995
—	2015 DZ53	0.19620	0.87013	20.8	0.40446	0.20443
—	2010 VA12	0.19875	0.84334	19.5	0.07376	0.22421
—	1996 BT	0.19978	0.83500	23.0	0.10126	0.37595
153201	2000 WO107	0.19985	0.78072	19.3	0.19124	0.35397
139289	2001 KR1	0.19996	0.84123	17.6	0.02376	0.47075
66391	1999 KW4	0.20010	0.68846	16.5	0.12587	0.20703
141079	2001 XS30	0.20015	0.82815	17.7	0.03979	0.20640
143637	2003 LP6	0.20341	0.88352	16.3	0.31278	0.51759
329915	2005 MB	0.20411	0.79284	17.1	0.33105	0.54317
438116	2005 NX44	0.20495	0.90745	17.3	0.35076	0.81328
369296	2009 SU19	0.20935	0.89942	17.9	0.06908	0.26797
184990	2006 KE89	0.21144	0.79925	16.4	0.14092	0.52566
—	2004 LG	0.21250	0.89714	18.0	0.39704	0.38711
—	2005 GL9	0.22226	0.89620	17.1	0.03307	0.22339
137052	Tjelvar	0.23768	0.80955	16.9	0.08579	0.24021
225416	1999 YC	0.24099	0.83050	17.2	0.29616	0.31271
—	2000 SG8	0.24508	0.90066	17.5	0.59763	0.75514
242643	2005 NZ6	0.24872	0.86443	17.4	0.08031	0.81175
136874	1998 FH74	0.25390	0.88462	15.7	0.29403	0.29322
40267	1999 GJ4	0.25669	0.80825	15.4	0.31560	0.25078
—	2011 WS2	0.25890	0.74356	17.2	0.16082	0.32279
—	2007 VL243	0.26200	0.72856	17.8	0.04606	0.46376
331471	1984 QY1	0.26348	0.89453	15.4	0.28198	0.34163
—	2006 OS9	0.26379	0.90377	17.8	0.21360	0.35270
369452	2010 LG14	0.26898	0.74267	17.9	0.32184	0.36409
190119	2004 VA64	0.27010	0.89042	17.1	0.41024	0.37468
351370	2005 EY	0.27510	0.89066	17.2	0.12769	0.27657
164201	2004 EC	0.28058	0.85954	15.7	0.12414	0.28329
385402	2002 WZ2	0.28476	0.88432	17.0	0.47899	0.34397
397237	2006 KZ112	0.28545	0.88694	16.7	0.75831	0.66348
253106	2002 UR3	0.28549	0.79295	16.4	0.52059	0.66113
364877	2008 EM9	0.29101	0.85153	17.3	0.08666	0.34927
—	2014 MR26	0.29387	0.76593	17.8	0.12435	0.66948
231937	2001 FO32	0.29523	0.82644	17.7	0.20666	0.32020
99907	1989 VA	0.29525	0.59468	17.9	0.24233	0.31057
170502	2003 WM7	0.29648	0.88027	17.2	0.20954	0.77615
—	2010 KY127	0.29686	0.88116	17.0	0.51914	0.36652
162269	1999 VO6	0.29734	0.73809	17.0	0.26966	0.34300
141525	2002 FV5	0.29916	0.72475	17.9	0.21795	0.33586

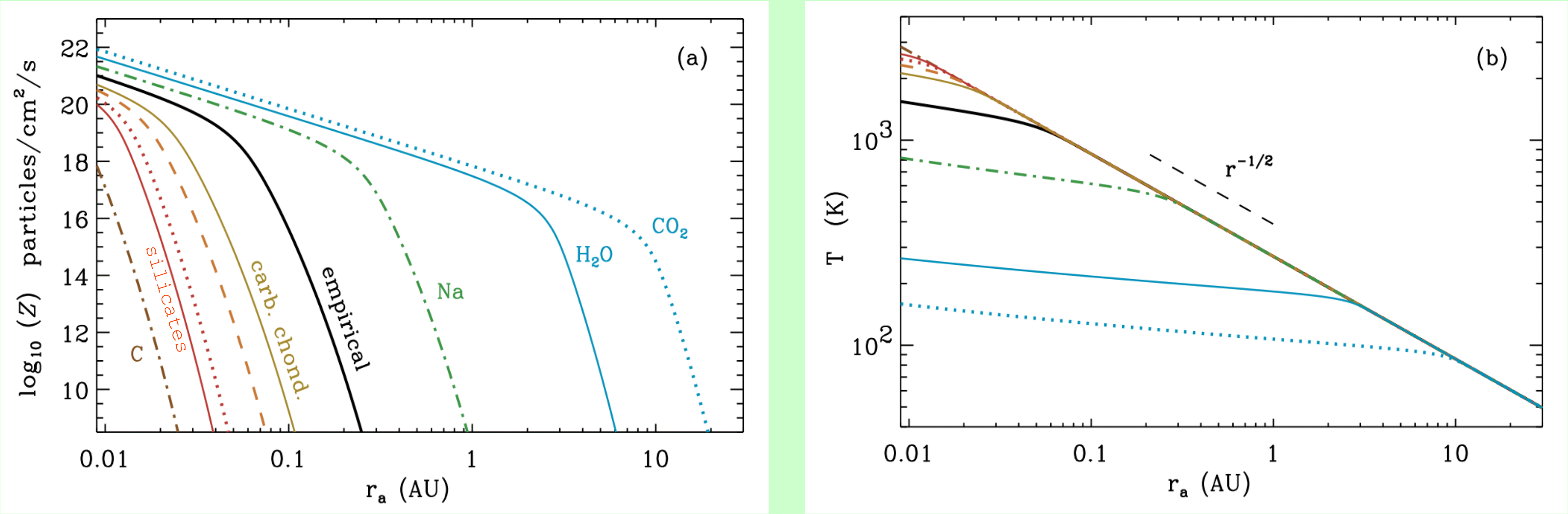
Asteroid physical properties

- Diameters range between 0.07 and 5 km (median: 0.89 km).
- Angular sizes (from WISPR) are < 0.1 arcsec, so the asteroids are definitely unresolved in WISPR's large (~1 arcmin) pixels.
- Apparent magnitudes (m_V) were converted into on-sky fluxes (F) and compared with expected zodiacal light background fluxes (F_Z).
- Previous work with SECCHI (DeForest et al. 2011) showed that faint signals of order $F/F_Z \approx 10^{-4}$ can be detected via sophisticated image processing.
- If WISPR is similar, 76 out of the 97 asteroids will be detectable.



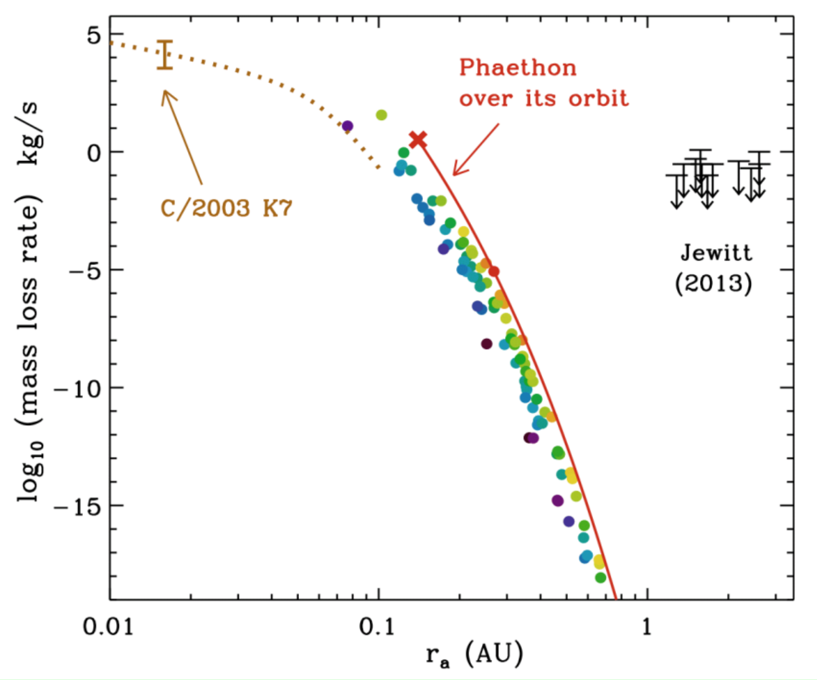
A model of inner heliospheric mass loss

- Comets lose their "ices" (H_2O, CO, CO_2) via **sublimation,** but near-Sun asteroids have likely already lost these easily evaporated volatile surface layers.
- At $r \lesssim 0.2$ AU, equilibrium temperatures are high enough that "rocky" regolith layers (e.g., silicates, Fe/Mg-rich minerals, & carbonaceous chondrites) can sublimate!
- We evaluated sublimation rates Z for a number of expected rocky substances using thermal energy balance: **solar radiation → thermal re-radiation + sublimation**



A model of inner heliospheric mass loss

- We still do not know the surface composition of active asteroids, so we decided to vary the chemical properties freely until finding agreement with the observed mass loss from Phaethon (Jewitt et al. 2013).
- Result: something with latent heat 204 kJ/mol, mean molecular weight 100 g/mol.
- Our paper's referee questioned our use of "ghost matter," but this was the same empirical procedure used by Sekanina (2003) to constrain the chemical properties of the (otherwise unknown!) material lost by sungrazing comets.
- The resulting properties appear to fall between atomic **sodium** (*L* ≈ 106 kJ/mol) and **carbonaceous chondrites** (*L* ≈ 250 to 350 kJ/mol), and may point to the existence of a heterogeneous mixture of multiple solid species on asteroid surfaces.
- Predicted gas mass loss rates for all 97 asteroids at d_{min}, also showing agreement with other comet data (C/2003 K7; Ciaravella et al. 2010). →



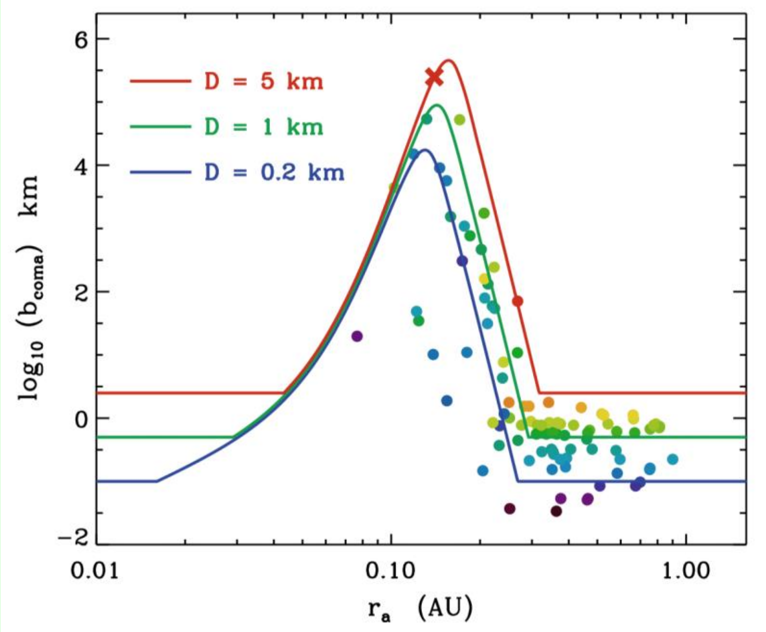
Dusty coma production: theory

- Conjecture: both gas & dust (with a broad range of grain sizes) of the *same* substance is ejected simultaneously. Free parameter: dust/gas mass ratio $\mathscr{M}$.

- This is different from the standard cometary scenario (where icy gas "drags out" silicate dust), but there are several analogous situations:
  - **comets** lose both gas-phase ice & larger "snows" (Protopapa et al. 2014);
  - ablating **meteors** lose fragments from nm "smoke" to cm "pebbles;"
  - near-star **exoplanets** may be disintegrating via gas & dust emission (Rappaport et al. 2012; van Lieshout et al. 2014).

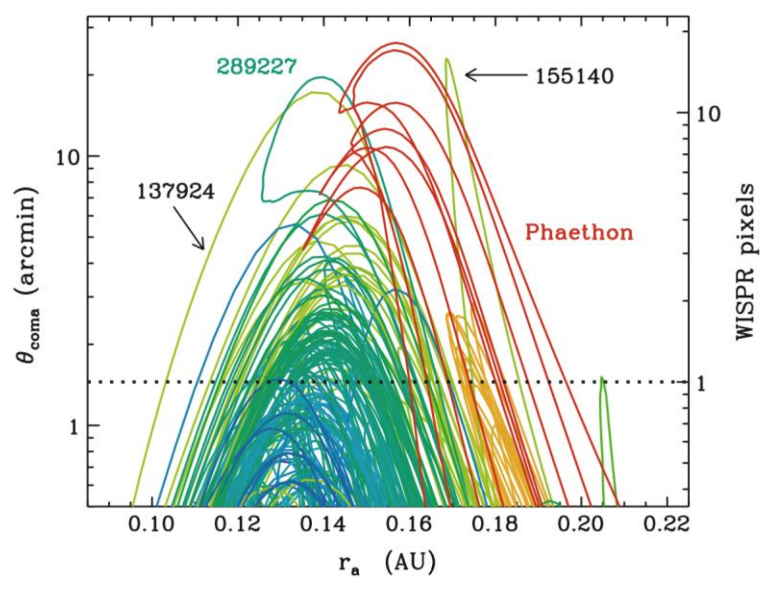
- Given values of $\mathscr{M}$, grain outflow speed, & grain size, we can predict the radial **number density profile of dust grains** surrounding a sublimating asteroid.

- Like above with the mass loss rate, we used Phaethon's observed tail size (Jewitt et al. 2013) to "calibrate" the parameters and predict observable ($F > 10^{-4} F_Z$) coma radii, expressed as impact parameter b_{coma} →

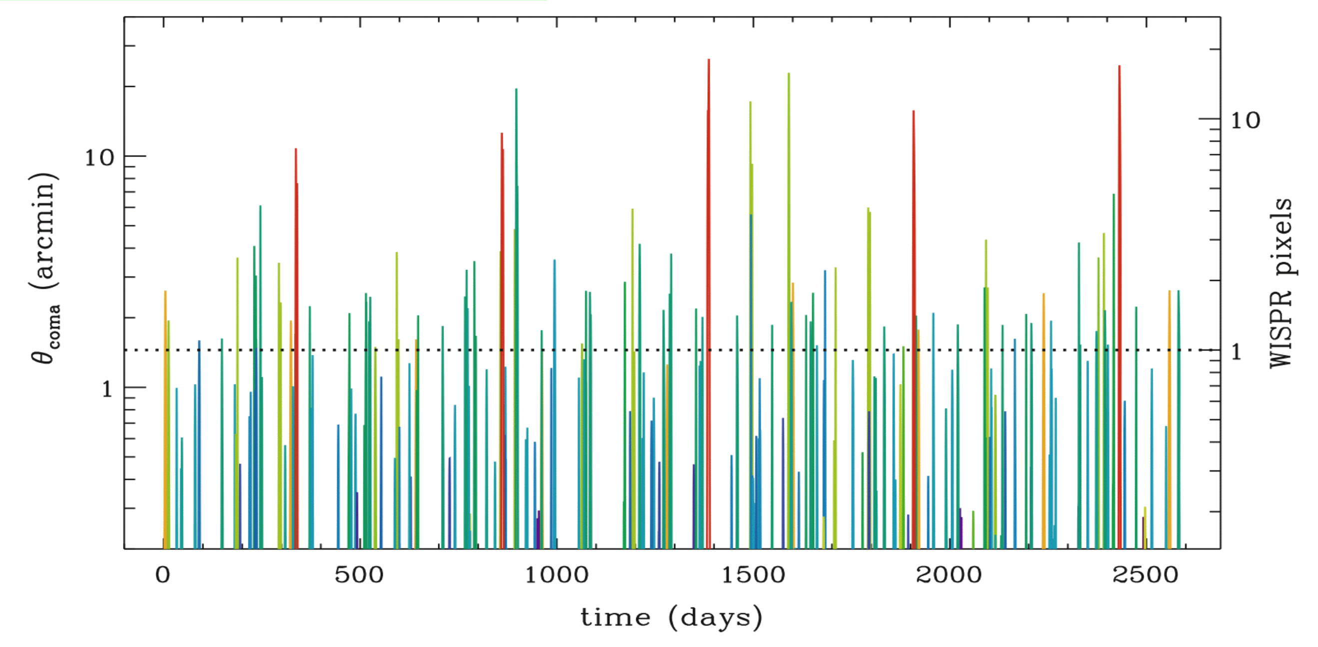


Dusty coma production: results

- Can SPP/WISPR resolve some of these predicted coma sizes? Yes!
- Converting b_{coma} to on-sky angular size θ_{coma}, we see several “events” for which the expected size is > several WISPR pixels.
- The paper gives a detailed tabular list of all 41 predicted events with $\theta_{\mathrm{coma}} > 3$ arcmin.



- ***Note:*** to be conservative, we err on the side of <u>under</u>estimating θ_{coma} by using the “radius” numbers instead of “diameters.”



Conclusions

Why do we care?

- Observations of dusty coma-like clouds around active asteroids at ~0.1 AU can put improved constraints on our knowledge about primordial solar system material in hot (i.e., seldom probed!) environments.
- Mass loss from solid bodies in the inner heliosphere also probes the small-scale turbulent dynamics of the solar wind (Brandt & Snow 2000; Huebner et al. 2007; Raymond et al. 2014).

Several things need improving:

- WISPR's field of view is occulted by SPP's heat shield & other structures, so it is not yet known if each predicted event would be observable.
- If SPP's launch date slips, the dates of mutual events need to be recalculated.
- Our spherical dust-coma model should be replaced by 3D coma/tail dynamics.

Our paper has been published online at *Earth, Moon, & Planets.*

Preprint: **`http://arXiv.org/abs/1606.01785`**

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