Astronomy 101
The Solar System
Tuesday, Thursday
2:30-3:45 pm
Hasbrouck 20

Tom Burbine
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Course

- **Course Website:**
  - http://blogs.umass.edu/astron101-tburbine/
- **Textbook:**
  - **Pathways to Astronomy (2nd Edition)** by Stephen Schneider and Thomas Arny.
  - **You also will need a calculator.**

Office Hours

- Mine
- Tuesday, Thursday - 1:15-2:15pm
- Lederle Graduate Research Tower C 632

- Neil
- Tuesday, Thursday - 11 am-noon
- Lederle Graduate Research Tower B 619-O

Homework

- We will use Spark
- https://spark.oit.umass.edu/webct/logonDisplay.dowebct
- Homework will be due approximately twice a week

Astronomy Information

- Astronomy Help Desk
- Mon-Thurs 7-9pm
- Hasbrouck 205
-

  The Observatory should be open on clear Thursdays
- Students should check the observatory website at: http://www.astro.umass.edu/~orchardhill for updated information
- There's a map to the observatory on the website.

Final

- Monday - 12/14
- 4:00 pm
- Hasbrouck 20

HW #20 and 21

- Due next Tuesday

Exam #4

- This Thursday
- Covers material from November 10-24

- Review Session – Wed. at 6 pm in Hasbrouck 134

What’s the difference?

- Asteroids
- Comets
- Meteorites

What’s the difference?

- Asteroids - small, solid objects in the Solar System
- Comets - small bodies in the Solar System that (at least occasionally) exhibit a coma (or atmosphere) and/or a tail
- Meteorites - small extraterrestrial body that reaches the Earth's surface

Why are these things important?

Why are these things important?

- These things can hit us (and possibly kill us)
- They are records of the early solar system
- They could be sources of material for mining

Moon

Record of Early Solar System

- Meteorites usually have ages of ~4.6 billion years
- Asteroids and comets are thought to be the building blocks of the terrestrial planets

Resources

- In outer space, it may be easier (and less expensive) to extract raw materials from asteroids or comets then to bring them from Earth
- Raw materials include water, iron, aluminum, chromium

Meaning of Asteroid

- Asteroid means “star-like”
- Called vermin of the sky by astronomers

216 Kleopatra

Asteroid Flyby

- Movie
- Images of 2002 NY40 on August 15-16
- Asteroid has diameter of 700 meters
- 524,000 kilometers from Earth (1.3 times the distance of the Earth to the Moon)
- Movie over 2 hour time period

951 Gaspra (taken by Galileo spacecraft)

- 20 x 12 x 11 km
- Galileo spacecraft flew by this asteroid

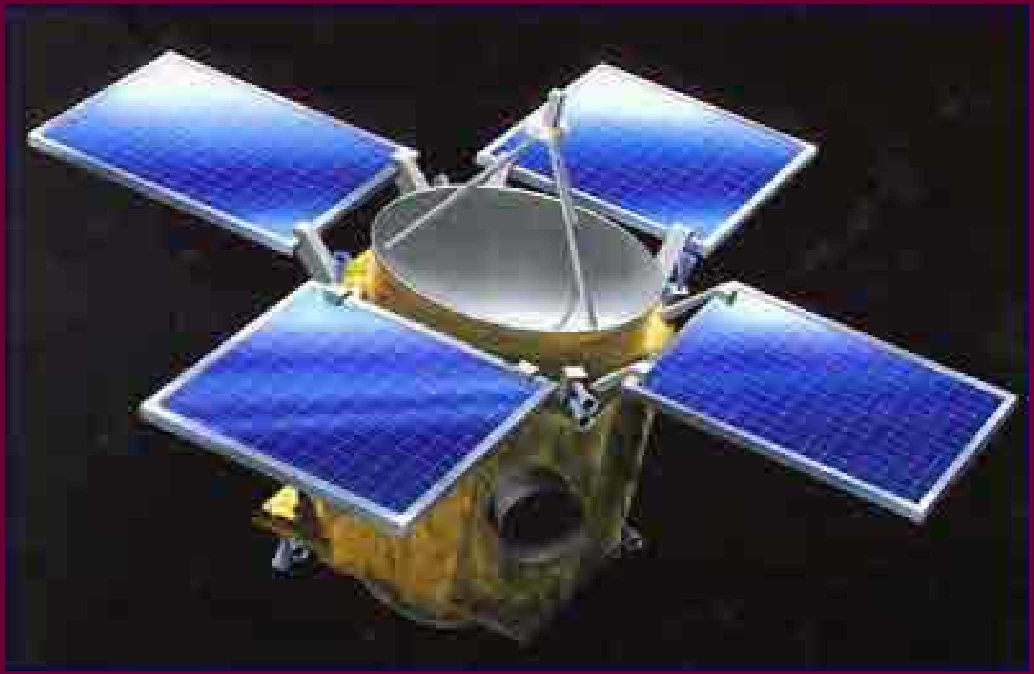
243 Ida (taken by Galileo spacecraft)

- 56 x 24 x 21 kilometers
- Galileo spacecraft flew by this asteroid

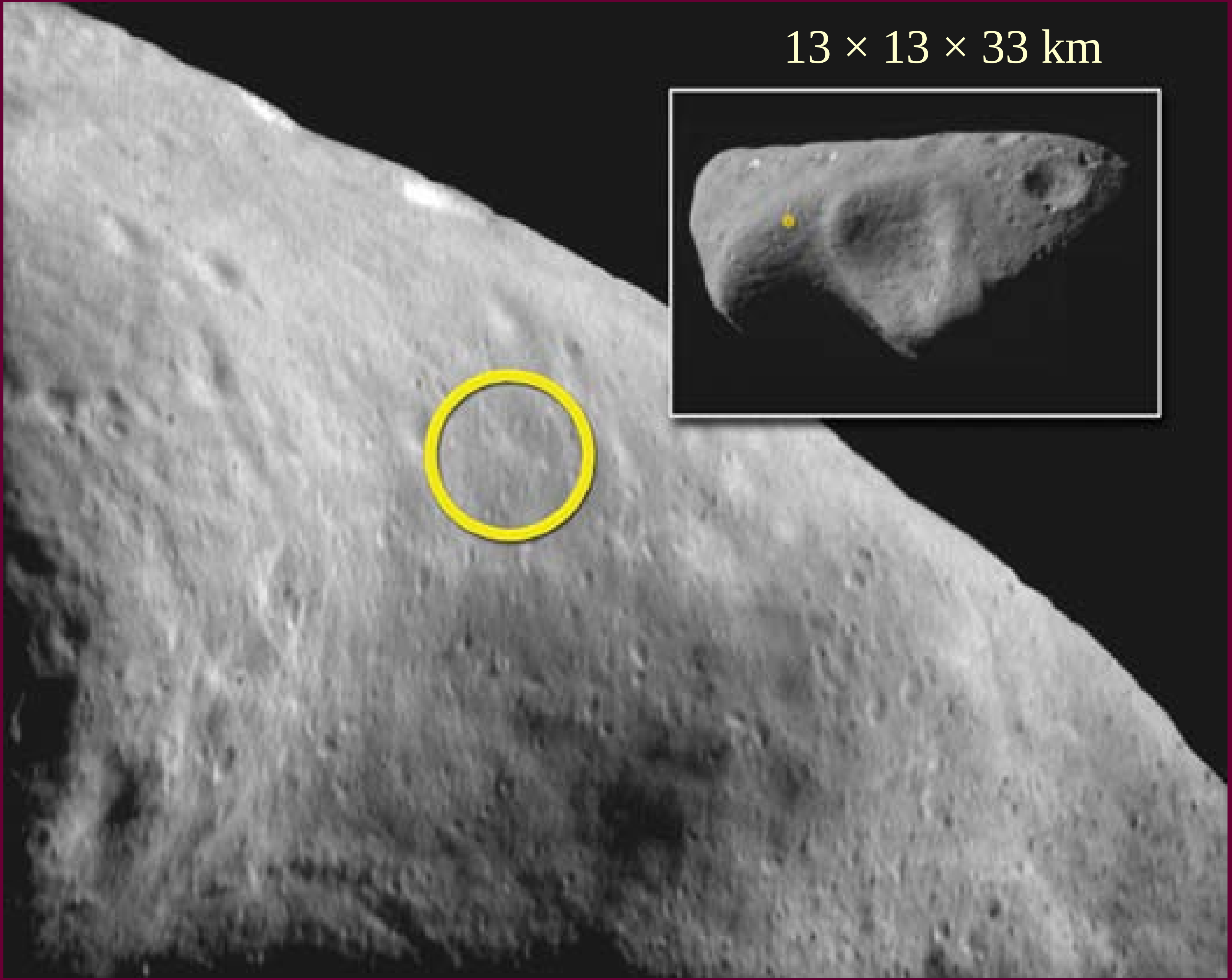
Ida has a satellite Dactyl

NEAR-Shoemaker mission to 433 Eros

- NEAR stands for Near-Earth Asteroid Rendezvous
- Shoemaker is for Gene Shoemaker



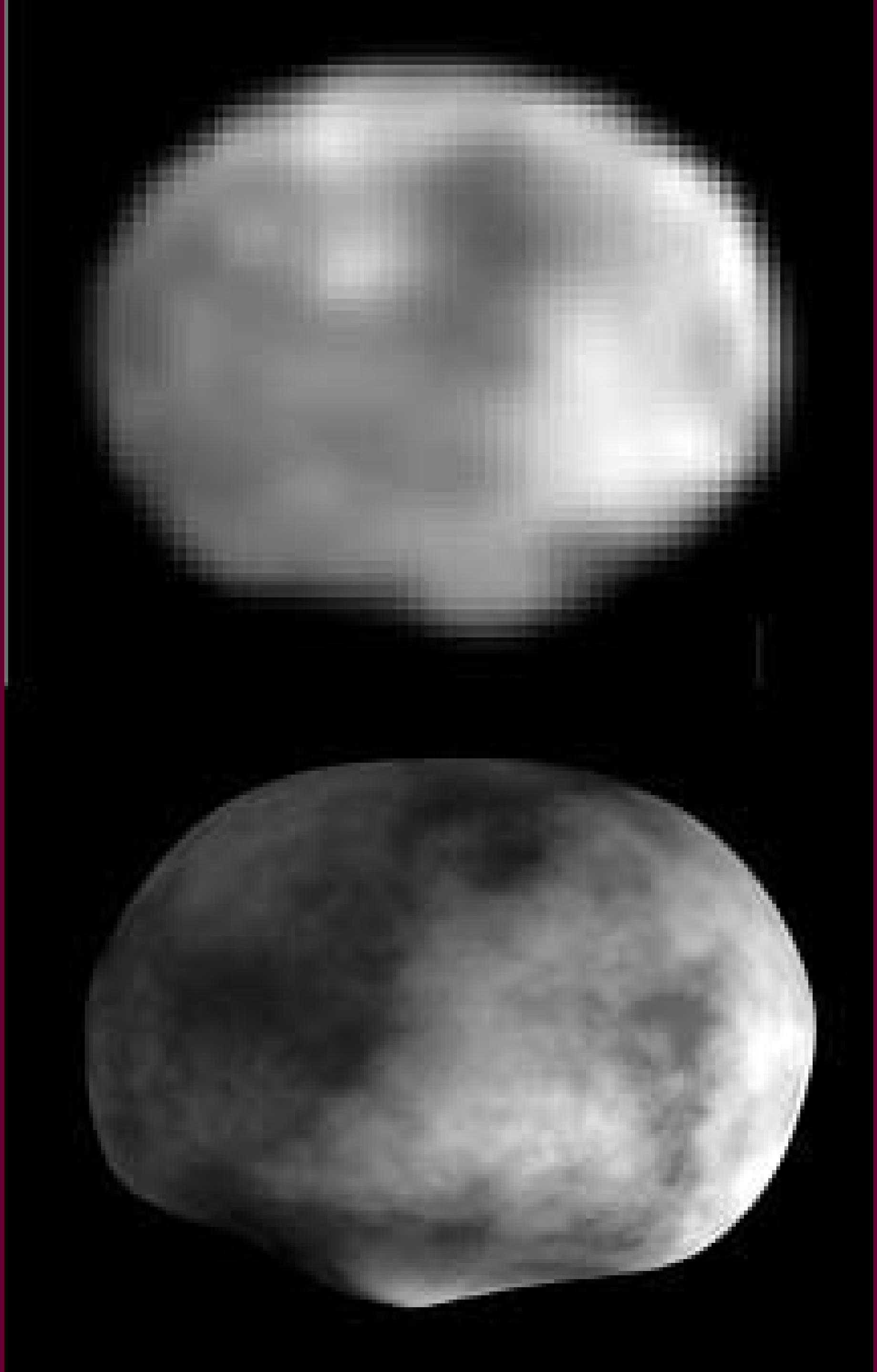
- Launch date: Feb. 17, 1996
- The first of four scheduled rendezvous burns on December 20, 1998 aborted due to a software problem
- Rendezvous delayed for a year
- Orbital insertion around Eros occurred on February 14, 2000


13 × 13 × 33 km

433 Eros

- Surface of 433 Eros
- Landing of NEAR-Shoemaker on Eros

Hubble Image of 4 Vesta



Dawn Spacecraft will visit 4 Vesta and 1 Ceres

- Launched September 27, 2007
- Will orbit Vesta in 2011-2012
- Will orbit Ceres in 2015

http://en.wikipedia.org/wiki/Image:Dawn_Flight_Configuration_2.jpg

Titius-Bode Law

- The mean distance *a* (AU) of the planet from the Sun:
- a = 0.4 + 0.3 x k
- where *k*=0,1,2,4,8,16,32,64,128 (0 followed by the powers of two)
- 1 astronomical unit (AU) is the average distance from the Earth to the Sun

Planet	(when discovered)	k	Titius-Bode Distance	Actual Distance
Mercury		0	0.4	0.39
Venus		1	0.7	0.72
Earth		2	1.0	1.00
Mars		4	1.6	1.52
?		8	2.8	?
Jupiter		16	5.2	5.20
Saturn		32	10.0	9.54
Uranus	(1781)	64	19.6	19.2
Neptune	(1846)	-	-	30.1
Pluto	(1930)	128	38.8	39.5

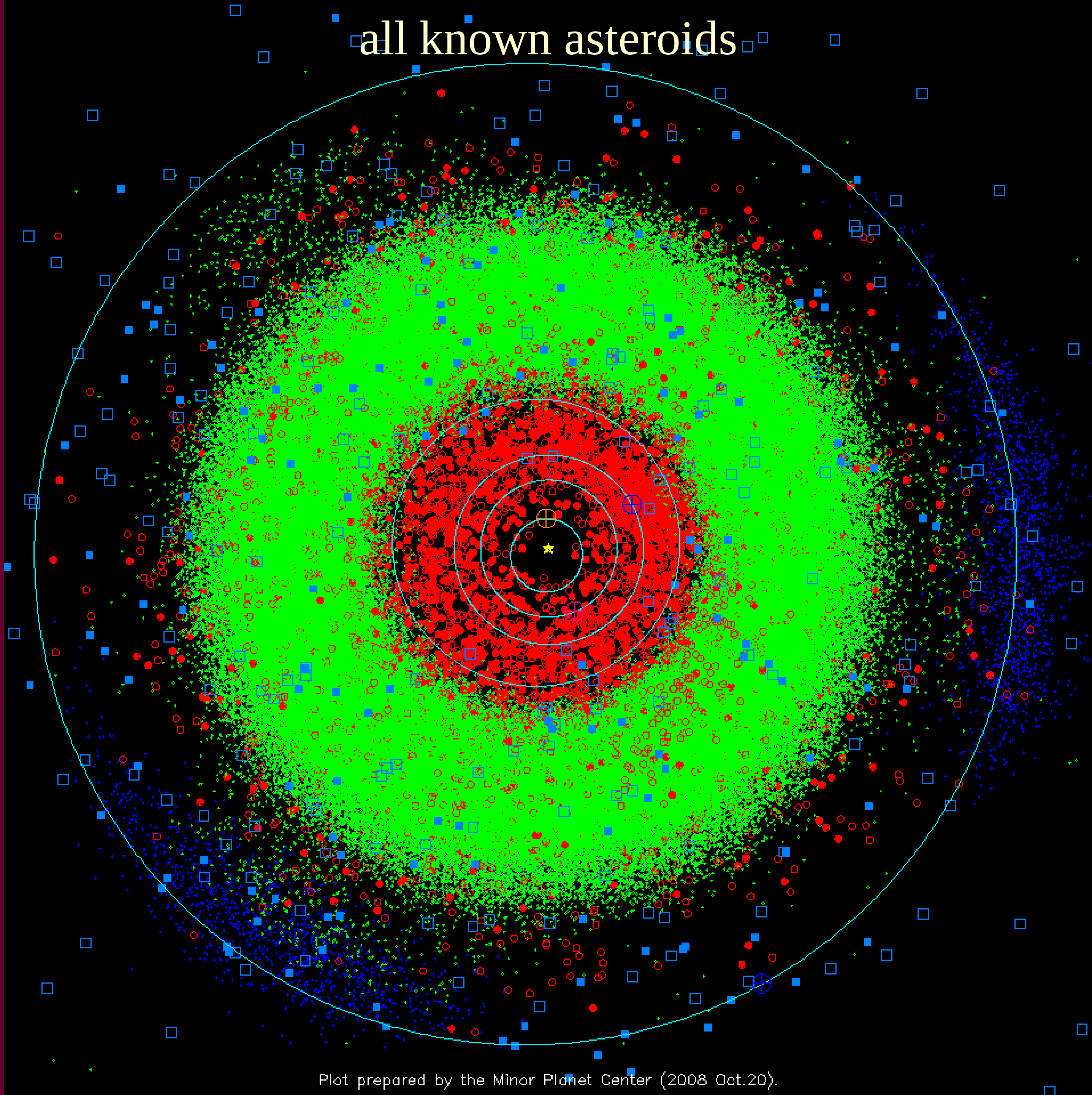
So …

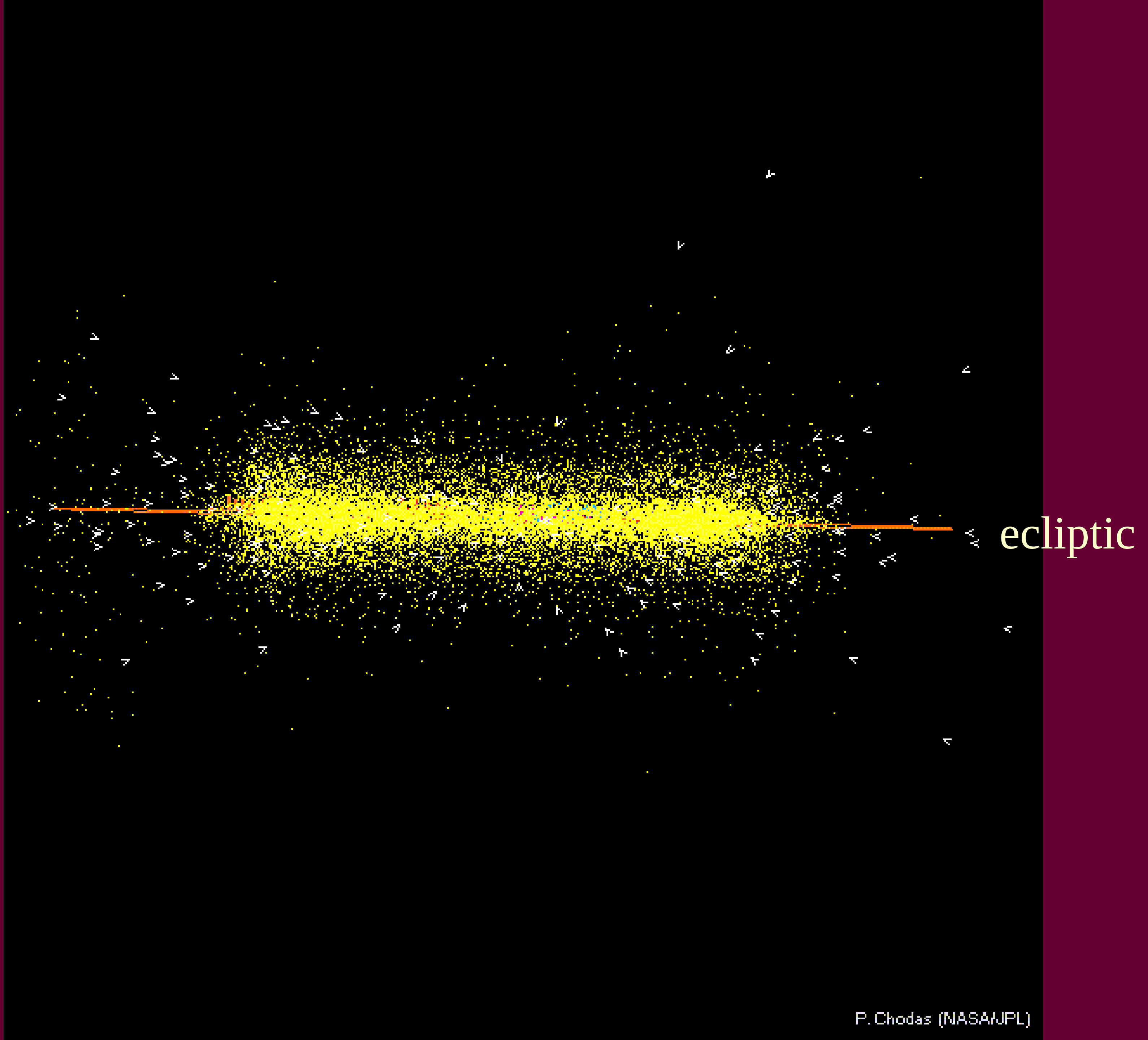
- Baron Franz Xaver von Zach organized a group of 24 astronomers to search the sky for the "missing planet"
- But the first asteroid, 1 Ceres, was not discovered by a member of the group, but rather by accident in 1801 by Giuseppe Piazzi

But …

- Three other asteroids (2 Pallas, 3 Juno, 4 Vesta) were discovered over the next few years (1802-1807)
- After eight more years of fruitless searches, most astronomers assumed that there were no more
- However, Karl Ludwig Hencke persisted, and began searching for more asteroids in 1830.
- Fifteen years later, he found 5 Astraea, the first new asteroid in 38 years. He also found 6 Hebe less than two years later.

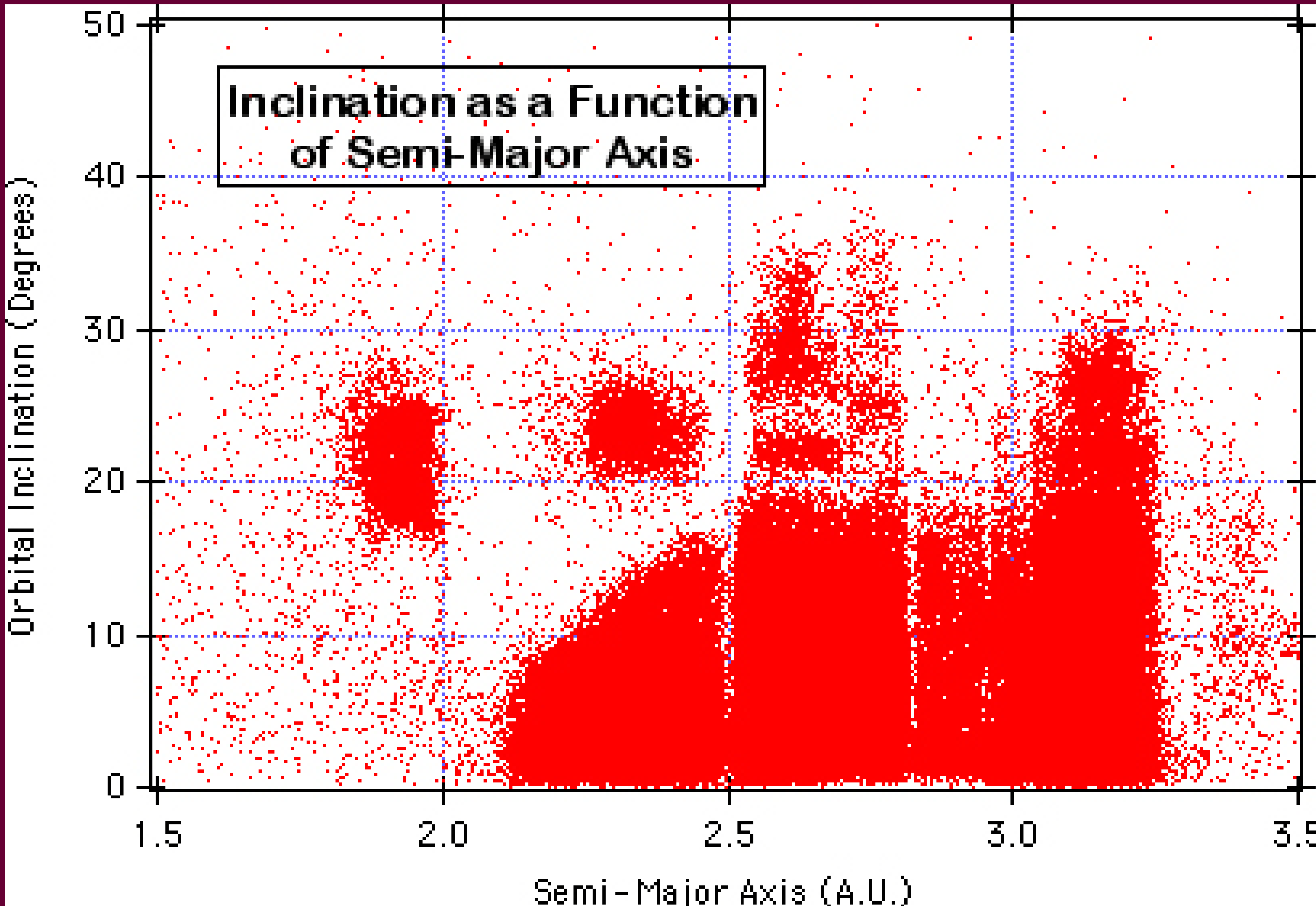
all known asteroids




ecliptic
P. Chodas (NASA/JPL)

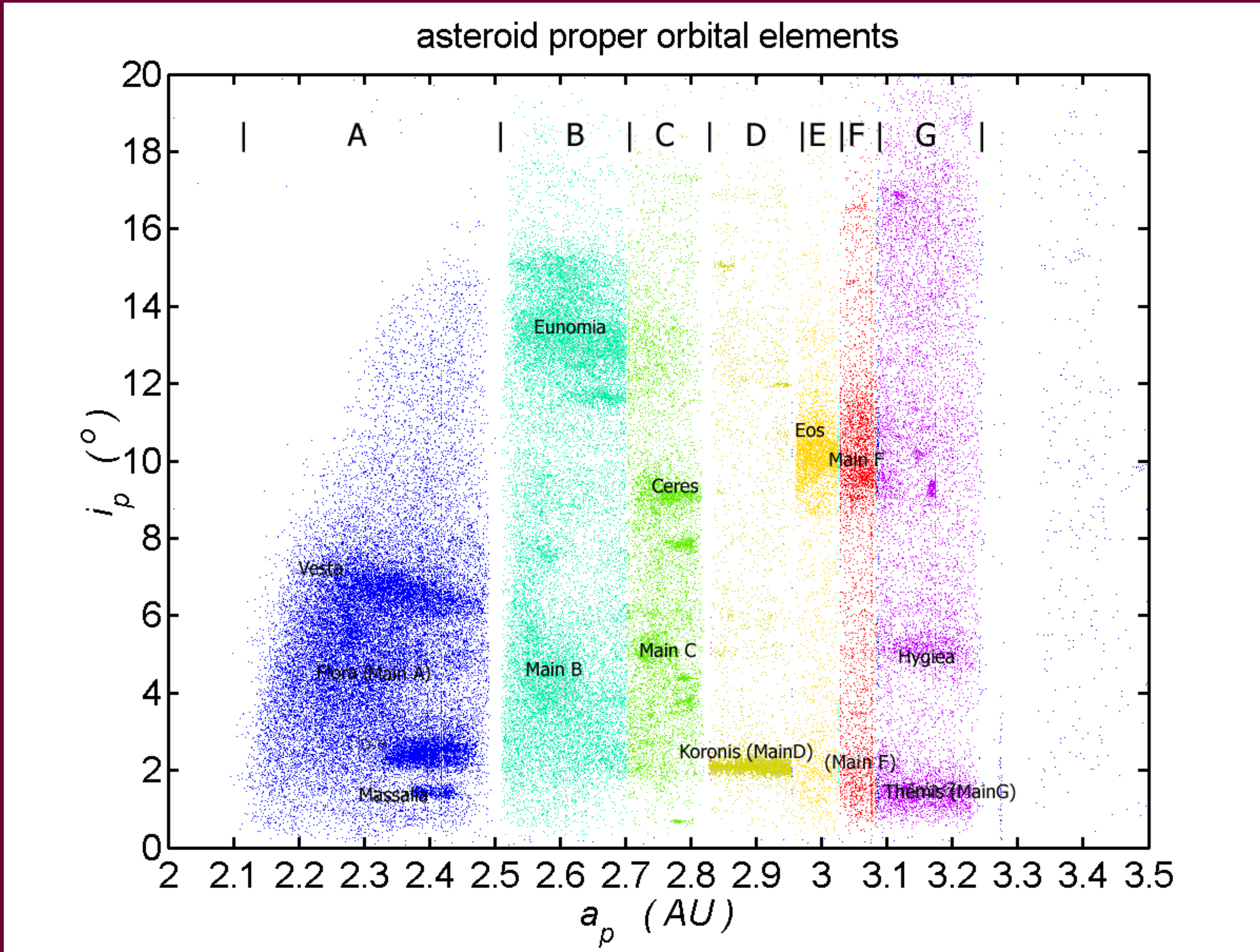
Currently

- Over 400,000 – number of known asteroids
- 6,610 – number of Near-Earth asteroids



Inclination as a Function
of Semi-Major Axis
Orbital Inclination (Degrees)
50
40
30
20
10
0
1.5
2.0
2.5
3.0
3.5
Semi-Major Axis (A.U.)

Asteroid Families



Asteroid Families

- Clumpings of asteroids with similar orbits
- Thought to be due to the breakup of a larger parent body

How are these objects named?

- Asteroids
  - After being observed on two consecutive nights, the object is given a provisional designation
  - a 4-digit number indicating the year
  - a space
  - a letter to show the half-month
  - another letter to show the order within the half-month
  - And an optional number to indicate the number of times the second letter has been repeated in that half-month period.
- For example, 1977 RG

Half Month Discovery

Letter	Dates	Letter	Dates
A	Jan. 1-15	B	Jan. 16-31
C	Feb. 1-15	D	Feb. 16-29
E	Mar. 1-15	F	Mar. 16-31
G	Apr. 1-15	H	Apr. 16-30
J	May 1-15	K	May 16-31
L	June 1-15	M	June 16-30
N	July 1-15	O	July 16-31
P	Aug. 1-15	Q	Aug. 16-31
R	Sept.1-15	S	Sept.16-30
T	Oct. 1-15	U	Oct. 16-31
V	Nov. 1-15	W	Nov. 16-30
X	Dec. 1-15	Y	Dec. 16-31

- I is omitted and Z is unused

Order within Month

- A = 1st B = 2nd C = 3rd D = 4th E = 5th
- F = 6th G = 7th H = 8th J = 9th K = 10th
- L = 11th M = 12th N = 13th O = 14th P = 15th
- Q = 16th R = 17th S = 18th T = 19th U = 20th
- V = 21st W = 22nd X = 23rd Y = 24th Z = 25th
- I is omitted

Asteroids discovered between Sept 16-30 of 1995

1995 SA	1
1995 SB	2
…	
1995 SY	24
1995 SZ	25
1995 SA1	26
…	
1995 SZ1	50
1995 SA2	51
…	
1995 SZ9	250
1995 SA10	251

Asteroid Numbers and Names

- When well-observed, asteroid is given a number
- 5159 1977 RG
- When was it discovered?

Asteroid Numbers

- When well-observed, asteroid is given a number
- 5159 1977 RG
- When was it discovered?
  - 1977
  - R Sept.1-15
  - G 7^{th} asteroid

Asteroid Names

- Then the discover gets to name it for period of 10 years or so
- 5159 1977 RG
- Was named

Asteroid Names

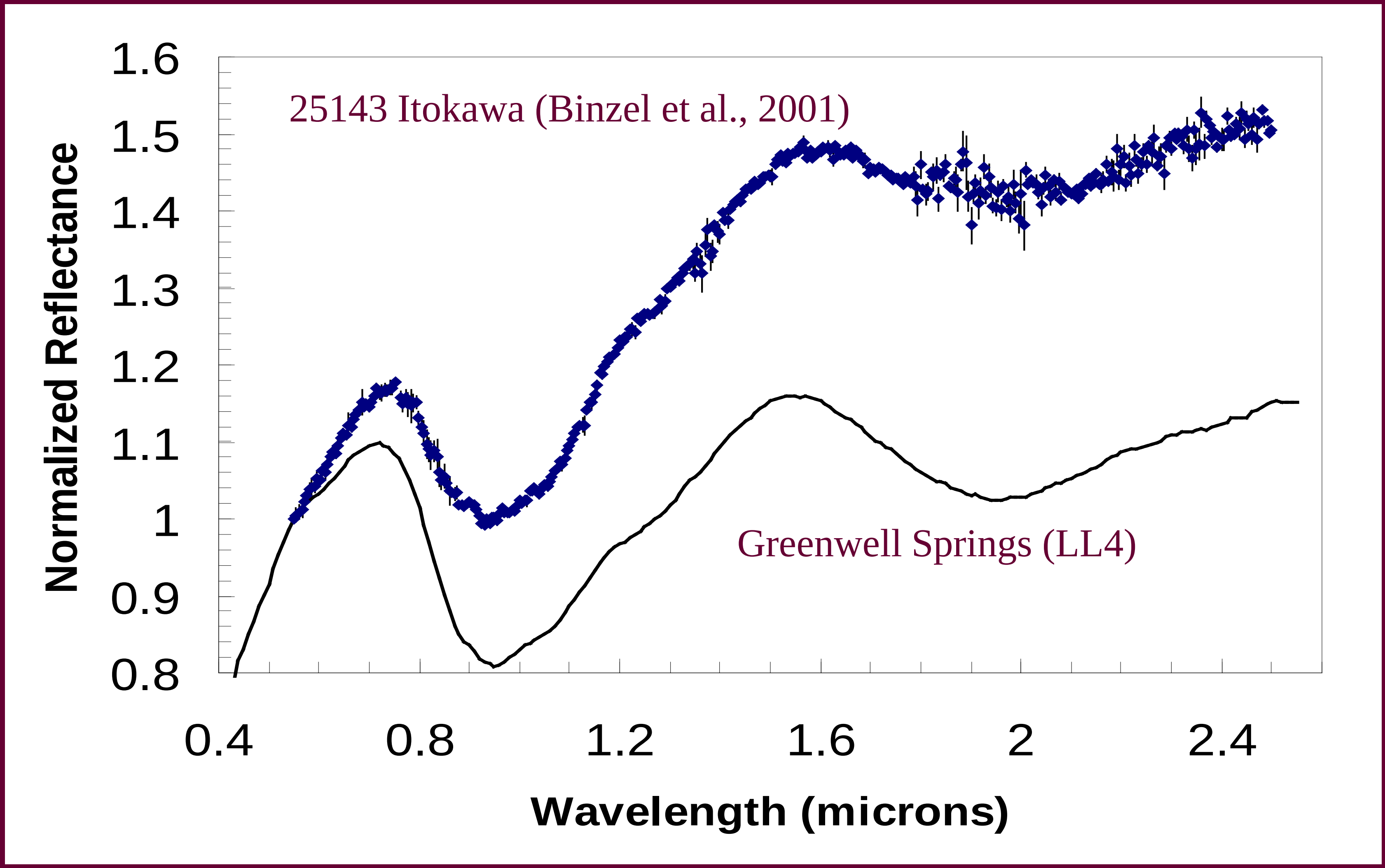
- Then the discover gets to name it for period of 10 years or so
- 5159 1977 RG
- Was named
  – 5159 Burbine

The Hayabusa Mission

Japanese mission to return a sample from an asteroid

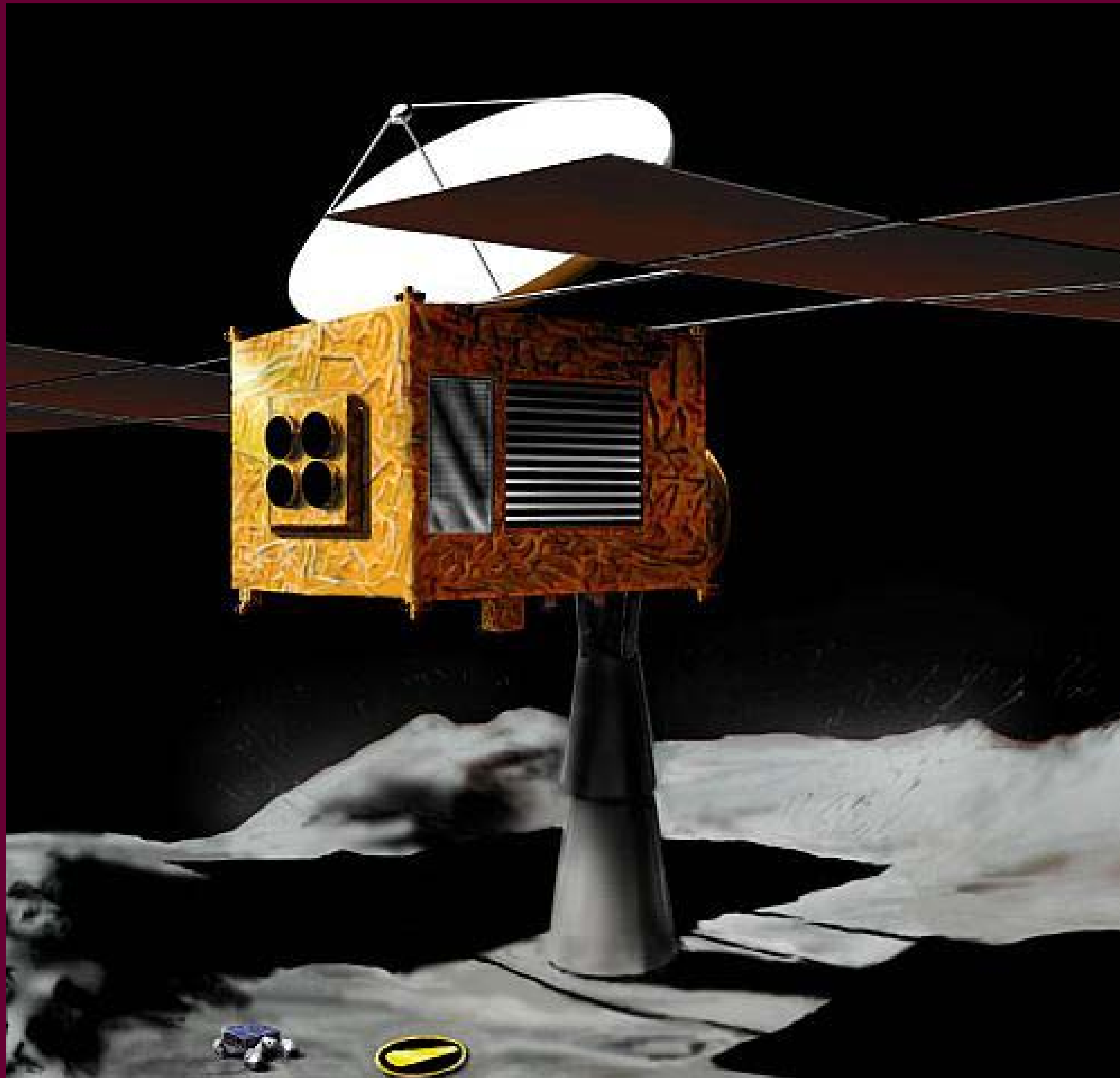

A.Ikeshita /MEF /ISAS

Hayabusa target



Mission Overview

- Hayabusa means ‘falcon’ in Japanese
- Mission Statement – “to bring back samples from and asteroid and investigate the mysteries of the Solar System”
- Launched May 9, 2003
- Flew to 25143 Itokawa (formerly 1998 SF36), named for Hideo Itokawa who was the father of the Japanese space program



Mission Goals

- Make contact with and land on Itokawa
- Gather samples of regolith on the surface
- Return samples to Earth for study
- Test new technologies for future missions
  - Ion engines
  - Autonomous navigation system - approaches the target far away without human guidance
  - Asteroid landing and sample collection system
  - Re-entry capsule system

Instrumentation

- XRS – X-ray based spectrometer
- ONC – Optical Navigation Camera
- LIDAR – LIght Detection And Ranger
- Minerva - MIcro/Nano Experimental Robot Vehicle for Asteroid, ‘hopper lander’
- Re-entry capsule – capable of withstanding heat 30 times that of the Apollo ship and forces 25 times the acceleration of gravity

- dimensions 540 meters by 270 meters by 210 meters

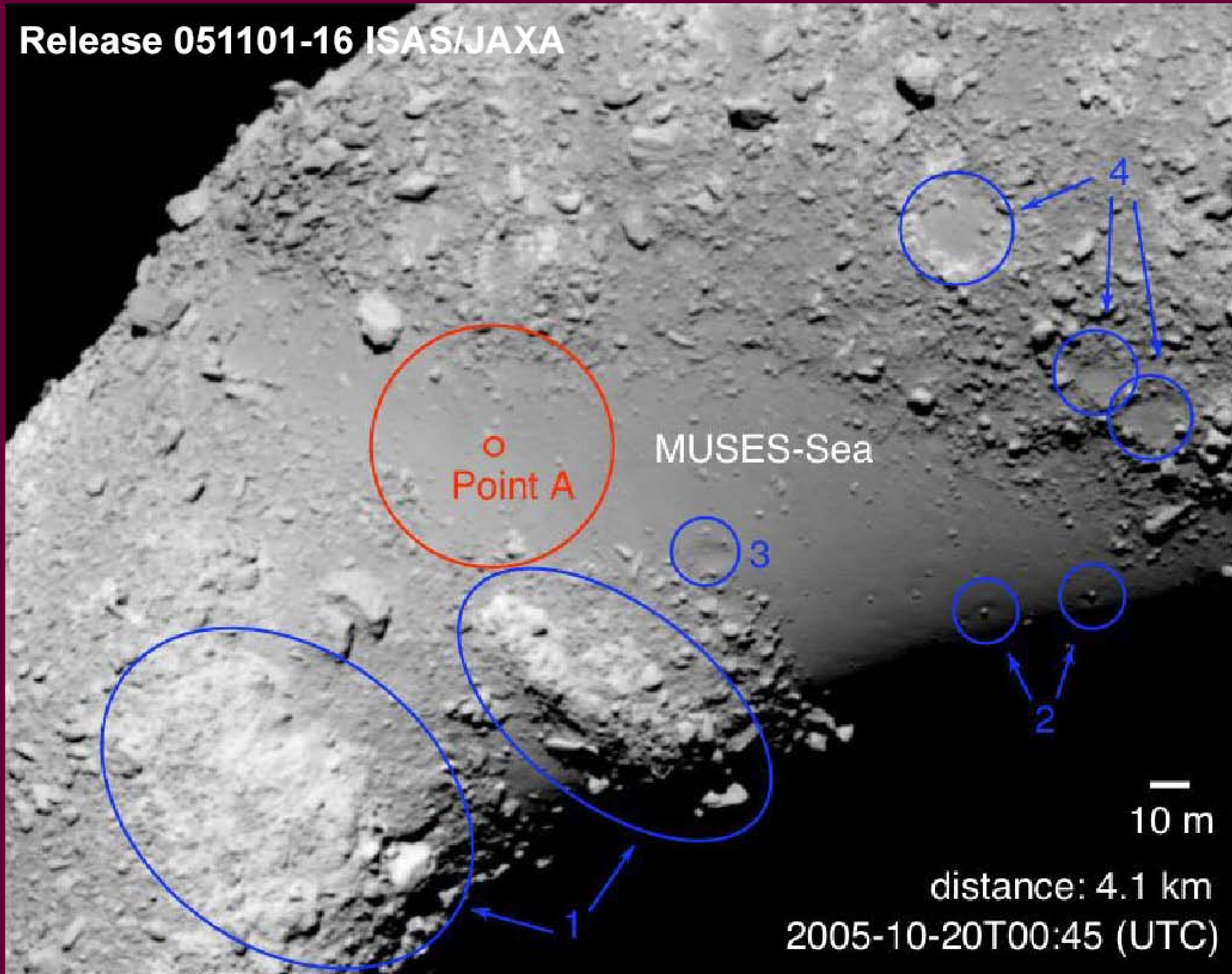


Fig. 11 MUSES-SEA Area, Site candidate-A.   Mountains, Boulders and Dimples, Craters.

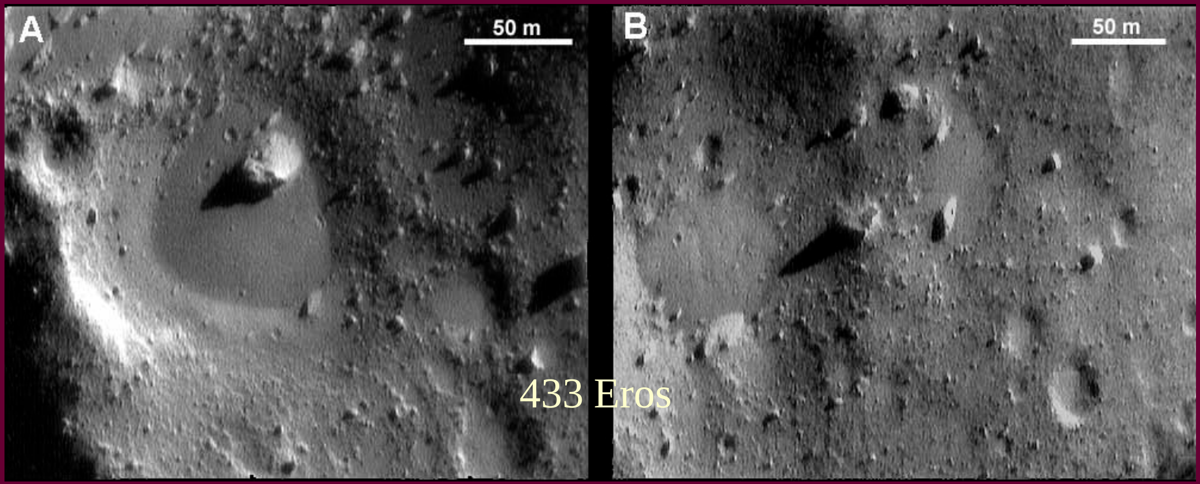
Asteroids as Geologic Bodies

- Asteroids are composed of different minerals
- Asteroids tend to be covered by craters
- Asteroids have a regolith (particulate surface)


25143 Itokawa (535 × 294 × 209 m)

http://homepage.ntlworld.com/heather.hobden1/Itokawa.jpg

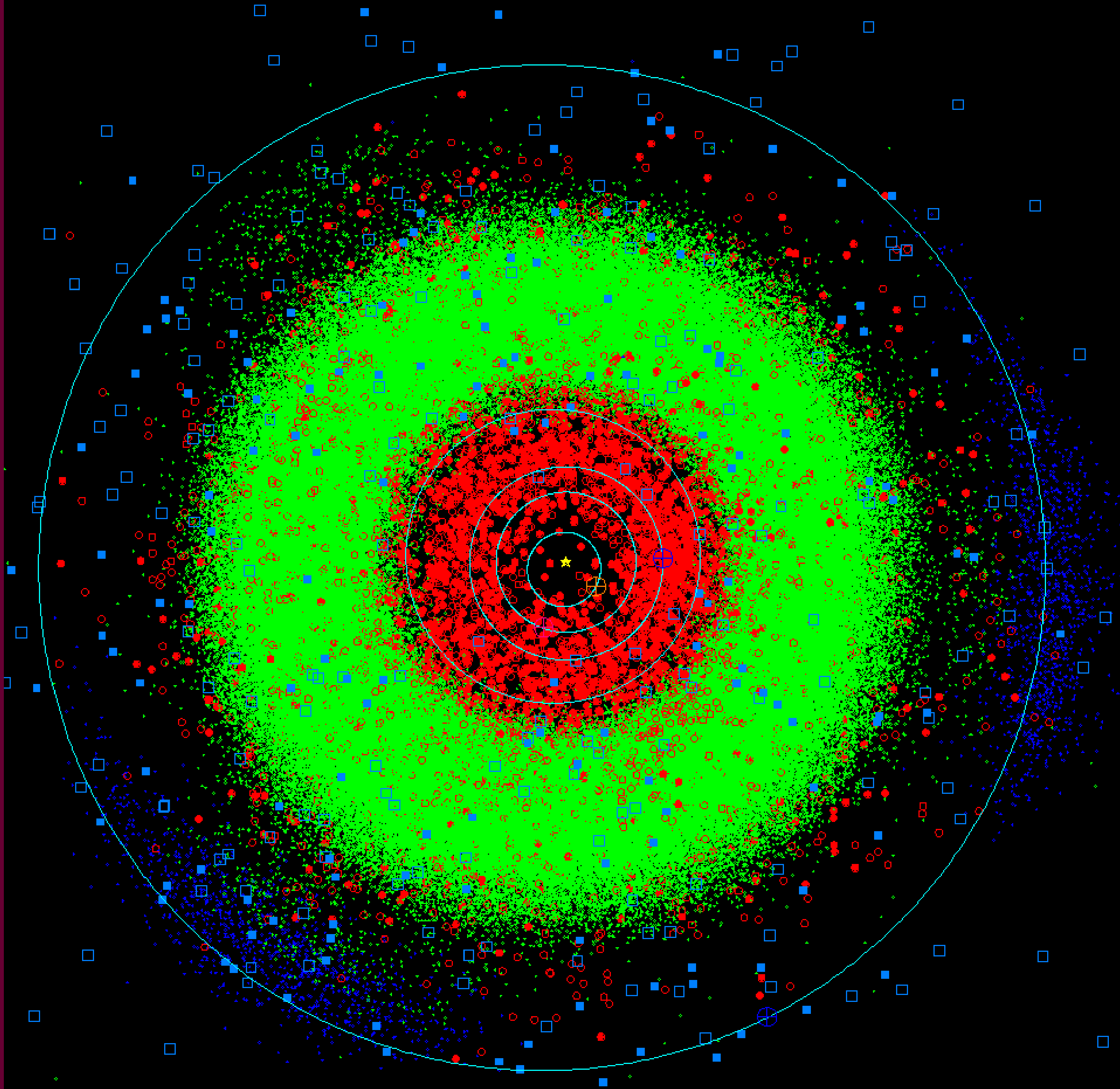
http://antwrp.gsfc.nasa.gov/apod/ap951020.html



433 Eros

http://www.astro.cornell.edu/~richardson/Seismic/ponds.gif

- 5565 objects are considered near-Earth asteroids
  - Their orbits come close to the Earth’s orbit
- More discovered every day



Plot prepared by the Minor Planet Center (2008 Sept 24)

1 AU = ~150 million kilometers
1 LD = Lunar Distance = ~384,000 kilometers

Object Name	Close Approach Date	Miss Distance (AU)	Miss Distance (LD)	Estimated Diameter	H (mag)	Relative Velocity (km/s)
(2001 UZ16)	2008-Sep-16	0.1523	59.3	350 m - 780 m	19.4	9.19
(2008 SR1)	2008-Sep-16	0.0400	15.6	240 m - 540 m	20.2	17.96
(2001 SQ3)	2008-Sep-17	0.0556	21.6	130 m - 280 m	21.6	15.27
(2008 RE1)	2008-Sep-17	0.0736	28.7	68 m - 150 m	23.0	6.72
(2003 SW130)	2008-Sep-19	0.0220	8.6	4.0 m - 8.9 m	29.1	8.17
(2008 SZ1)	2008-Sep-19	0.0308	12.0	32 m - 70 m	24.6	7.14
(2008 ST1)	2008-Sep-20	0.0038	1.5	11 m - 25 m	26.9	7.78
(2008 RT24)	2008-Sep-22	0.0739	28.7	35 m - 79 m	24.4	6.12
(2008 RW24)	2008-Sep-23	0.0129	5.0	71 m - 160 m	22.9	11.03
(2008 SA)	2008-Sep-23	0.0061	2.4	26 m - 58 m	25.0	7.79

Energy of an impact

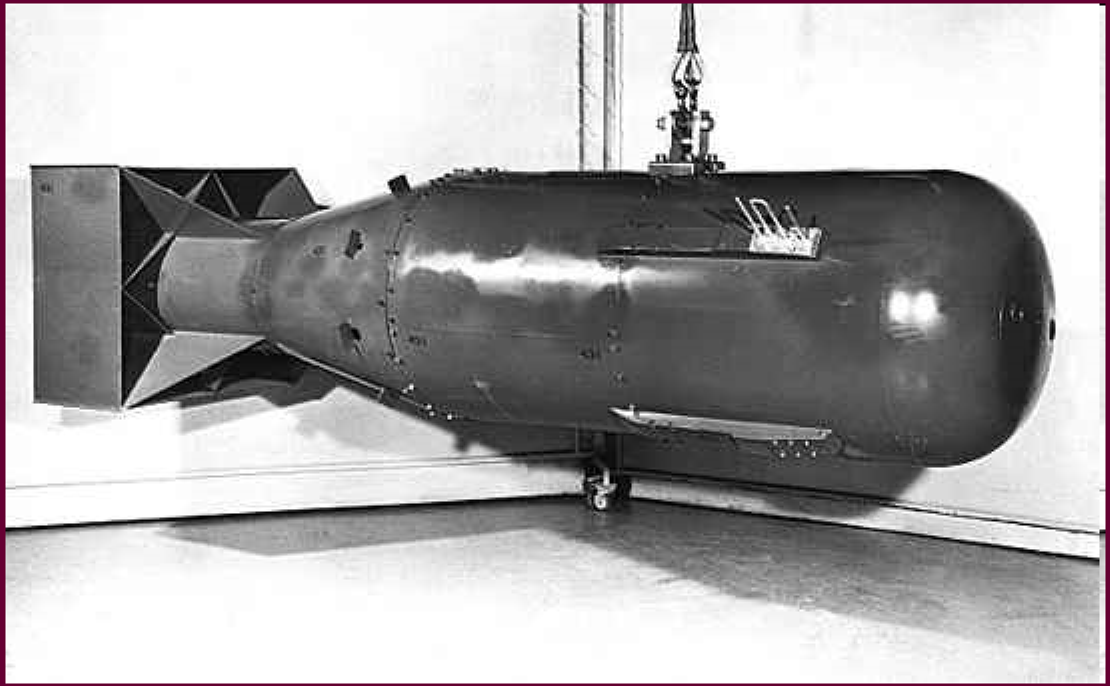
- $E = \frac{1}{2}mv^2$
- v = 10 km/s = 10,000 m/s
- $m = \rho V$
- $V = 4/3\pi r^3$
- 100 m object
  - $V = 4/3\pi(50)^3 = 5.2 \times 10^5\ m^3$
- 1,000 m object
  - $V = 4/3\pi(500)^3 = 5.2 \times 10^8\ m^3$
- 10,000 m object
  - $V = 4/3\pi(5000)^3 = 5.2 \times 10^{11}\ m^3$

Energy of an impact

- $E = \frac{1}{2} \rho V v^2$
- v = 10 km/s = 10,000 m/s
- 100 m diameter object
  - $E = \frac{1}{2} * 5.2 \times 10^5\ m^3 * (1 \times 10^8) * \rho$
- 1,000 m diameter object
  - $E = \frac{1}{2} * 5.2 \times 10^8\ m^3 * (1 \times 10^8) * \rho$
- 10,000 m diameter object
  - $E = \frac{1}{2} * 5.2 \times 10^{11}\ m^3 * (1 \times 10^8) * \rho$

Energy of Nuclear Bombs

- Usually given in Megatons of TNT
- The bomb that destroyed Hiroshima yielded ~0.015 Megatons (~15 kilotons) of TNT
- Largest nuclear bomb ever was ~50 Megatons (~3,400 Hiroshimas)



http://images.encarta.msn.com/xrefmedia/sharemed/targets/images/pho/t039/T039873A.jpg

Energy of an Impact

- ρ = 7,500 kg/m^3 for an iron meteorite
- 100 m diameter object
  - E = 2 x 10^{17} J = 47 MT of TNT ≈ 3,100 Hiroshimas
- 1,000 m diameter object
  - E = 2 x 10^{20} J = 4.7 x 10^{4} MT of TNT ≈ 3,100,000 Hiroshimas
- 10,000 m diameter object
  - E = 2 x 10^{23} J = 4.7 x 10^{7} MT of TNT ≈ 3,100,000,000 Hiroshimas

Energy of an Impact

- $\rho = 3{,}500\ kg/m^3$ for an ordinary chondrite
- 100 m diameter object
  - – $E = 9.2 \times 10^{16}$ J = 22 MT of TNT ≈ 1,500 Hiroshimas
- 1,000 m diameter object
  - – $E = 9.2 \times 10^{19}$ J = 2.2×10^{4} MT of TNT ≈ 1,500,000 Hiroshimas
- 10,000 m diameter object
  - – $E = 9.2 \times 10^{22}$ J = 2.2×10^{7} MT of TNT ≈ 1,500,000,000 Hiroshimas

The Effects

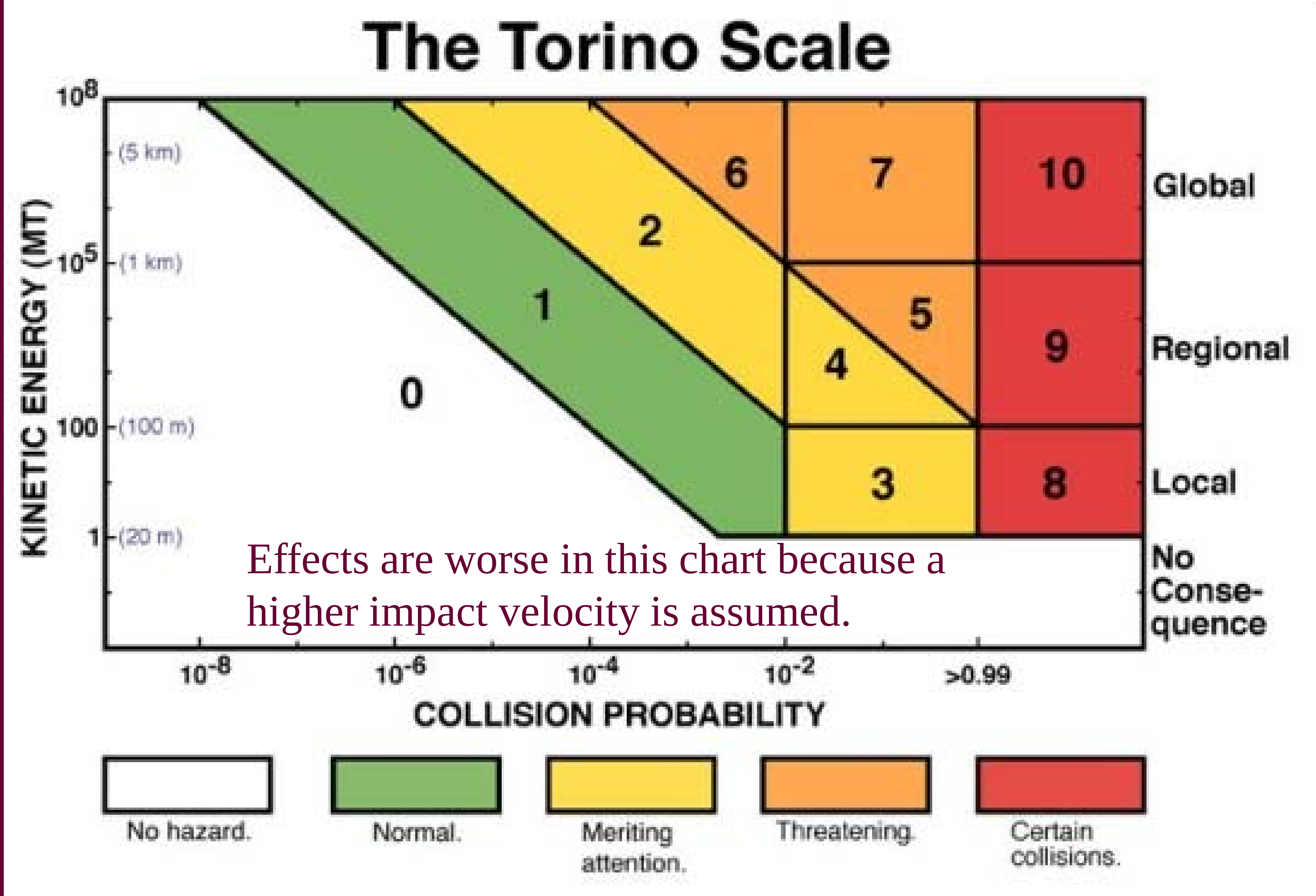
- If an 100-meter iron asteroid hit Hartford at 10 km/s:
- 2.3 km crater forms
- Here:
  - Richter Scale Magnitude: **5.7**
  - Shaking felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing cars rocked noticeably.
  - Shaking felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned.
  - At your position there is a fine dusting of ejecta with occasional larger fragments
  - Sound intensity will be as loud as heavy traffic.

The Effects

- If an 1-kilometer iron asteroid hit Hartford at 10 km/s:
- 15.7 km crater forms
- Here:
    - Richter Scale Magnitude: **7.7**
    - Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built structures; some chimneys broken.
    - The ejecta will arrive ~130 seconds after the impact.
    - The air blast will arrive at approximately 245 seconds. Multistory wall-bearing buildings will collapse. Wood frame buildings will almost completely collapse. Highway truss bridges will collapse. Glass windows will shatter. Up to 90 percent of trees blown down; remainder stripped of branches and leaves.

The Effects

- If an 10-kilometer iron asteroid hit Hartford at 10 km/s:
- 74.1 km crater forms
- Asteroid that killed off the dinosaurs was ~10 km in diameter
- Here:
  - Richter Scale Magnitude: 9.7 (greater than any impact in recorded history)
  - UMASS-Amherst is in the region which collapses into the final crater.



Effects are worse in this chart because a higher impact velocity is assumed.

http://www.aerospaceweb.org/question/astronomy/impact/torino-scale.jpg

Events Having No Likely Consequences	0	The likelihood of a collision is zero, or well below the chance that a random object of the same size will strike the Earth within the next few decades. This designation also applies to any small object that, in the event of a collision, is unlikely to reach the Earth's surface intact.
Events Meriting Careful Monitoring	1	The chance of collision is extremely unlikely, about the same as a random object of the same size striking the Earth within the next few decades.
Events Meriting Concern	2	A somewhat close, but not unusual encounter. Collision is very unlikely.
	3	A close encounter, with 1% or greater chance of a collision capable of causing localized destruction.
	4	A close encounter, with 1% or greater chance of a collision capable of causing regional devastation.
Threatening Events	5	A close encounter, with a significant threat of a collision capable of causing regional devastation.
	6	A close encounter, with a significant threat of a collision capable of causing a global catastrophe.
	7	A close encounter, with an extremely significant threat of a collision capable of causing a global catastrophe.
Certain Collisions	8	A collision capable of causing localized destruction. Such events occur somewhere on Earth between once per 50 years and once per 1000 years.
	9	A collision capable of causing regional devastation. Such events occur between once per 1000 years and once per 100,000 years.
	10	A collision capable of causing a global climatic catastrophe. Such events occur once per 100,000 years, or less often.

http://comp.uark.edu/~sboss/torinoscale.jpg

http://www.nature.com/nature/journal/v418/n6897/images/418468b-i1.0.jpg

What is important to know about possible incoming asteroids?

- Will it hit the Earth?
- Size?
- Where will it hit?
  - ocean? (You might get a tsunami)
  - uninhabited area?
  - major population center?
- What is it made out of?
  - That is what I work on
  - I try to determine the mineralogy of asteroids using meteorites as a guide.
- What will be its impacting velocity?

How could you deflect an asteroid?

- First a spacecraft could be crashed directly into the asteroid.
- Then a second spacecraft, a gravity tractor, would be used.
  - It would weigh around a ton and hovering about 150 meters away from the asteroid.
  - It would exert a gentle gravitational force, changing the asteroid's velocity by only 0.22 microns per second each day.

http://space.newscientist.com/article/dn14414-gravity-tractor-could-deflect-asteroids-nasa-study-says.html

Meteorite

- A small extraterrestrial body that reaches the Earth's surface

Why are meteorites important?

Why are meteorites important?

- They are primarily fragments of asteroids, which can hit us
- They are records of the early solar system

Moon

Meteorites

- Usually have ages of ~4.6 billion years
- Asteroids and comets are thought to be the building blocks of the terrestrial planets

Meteorites

- Many early cultures recognized (or believed) certain stones as having fallen from the sky
- Many early cultures had tools made from iron meteorites
- But to the scientists of the Renaissance and later periods, stones falling from the heavens were considered superstition or heresy

More evidence …

- In 1492, a meteorite weighing almost 130 kilograms landed near the town of Ensisheim, Alsace, France, then in the hands of Germany

Then ..

- In 1794, Ernst Friedrich Chladni, considered the father of meteoritics, published a book in which he concluded that stone and iron masses did fall out of the sky
- In 1803, thousands of meteorite fragments bombarded L'Aigle in Normandy, France, an event investigated by Jean-Baptiste Biot of the French Academy of Science.

Thomas Jefferson

- Meteorite landed in Weston, CT
- It was brought to Yale where it was concluded it was from outer space
- Thomas Jefferson, President of the United states, was told about it

And responded

- "Gentlemen, I would rather believe that two Yankee professors would lie than believe that stones fall from heaven."

Meteorites

- Named after a nearby geographic locality

Meteorite

- Esquel Pallasite
- Found in Esquel, Argentina

Meteorites

- Almost all are thought to be fragments of asteroids
- Where else can they come from?

Meteorites

- Almost all are thought to be fragments of asteroids
- Where else can they come from?
  - Moon - ~42 samples
  - Mars - ~34 samples
  - Comets?
  - Venus?
  - Mercury?
  - Other solar systems?

Peekskill Meteorite

- http://aquarid.physics.uwo.ca/~pbrown/Videos/peekskill.htm

Meteorites

- Meteorites are composed of different minerals
  - Silicates – contain silicon and oxygen
  - Sulfides – contain sulfur
  - Oxide – contains oxygen
  - Iron-nickel metal

Meteorites

- Usually named after the town (or nearest town) where they fell or were located

Falls and Finds

- Falls – see them fall
- Finds – find them

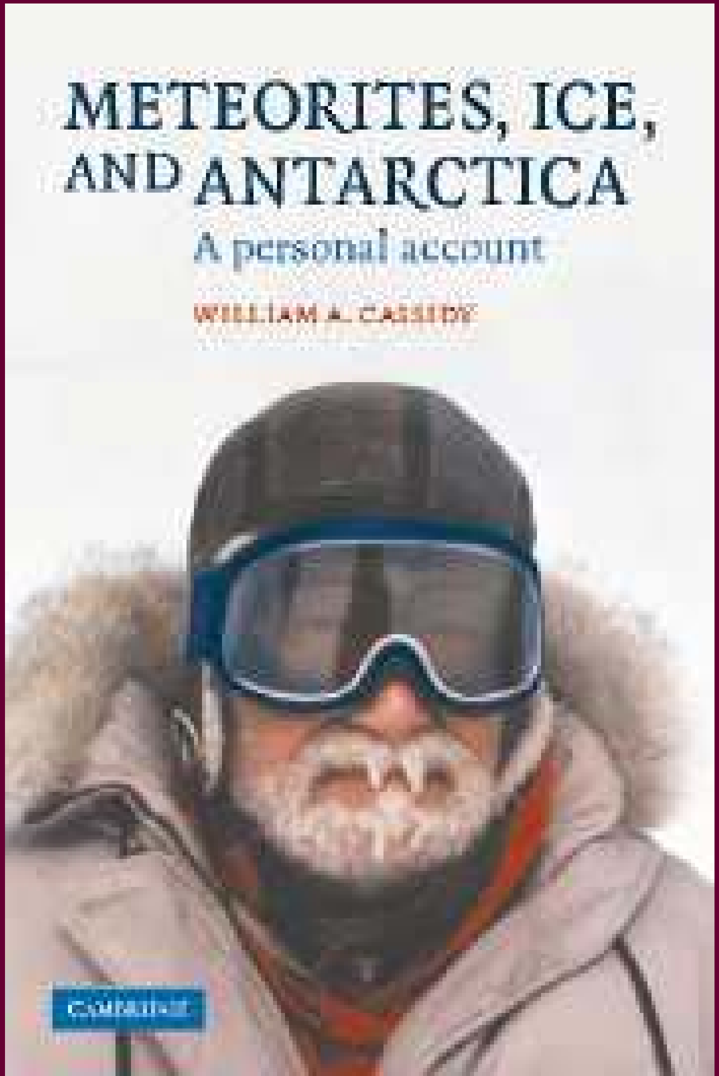
Fall Statistics (greater than 1%)

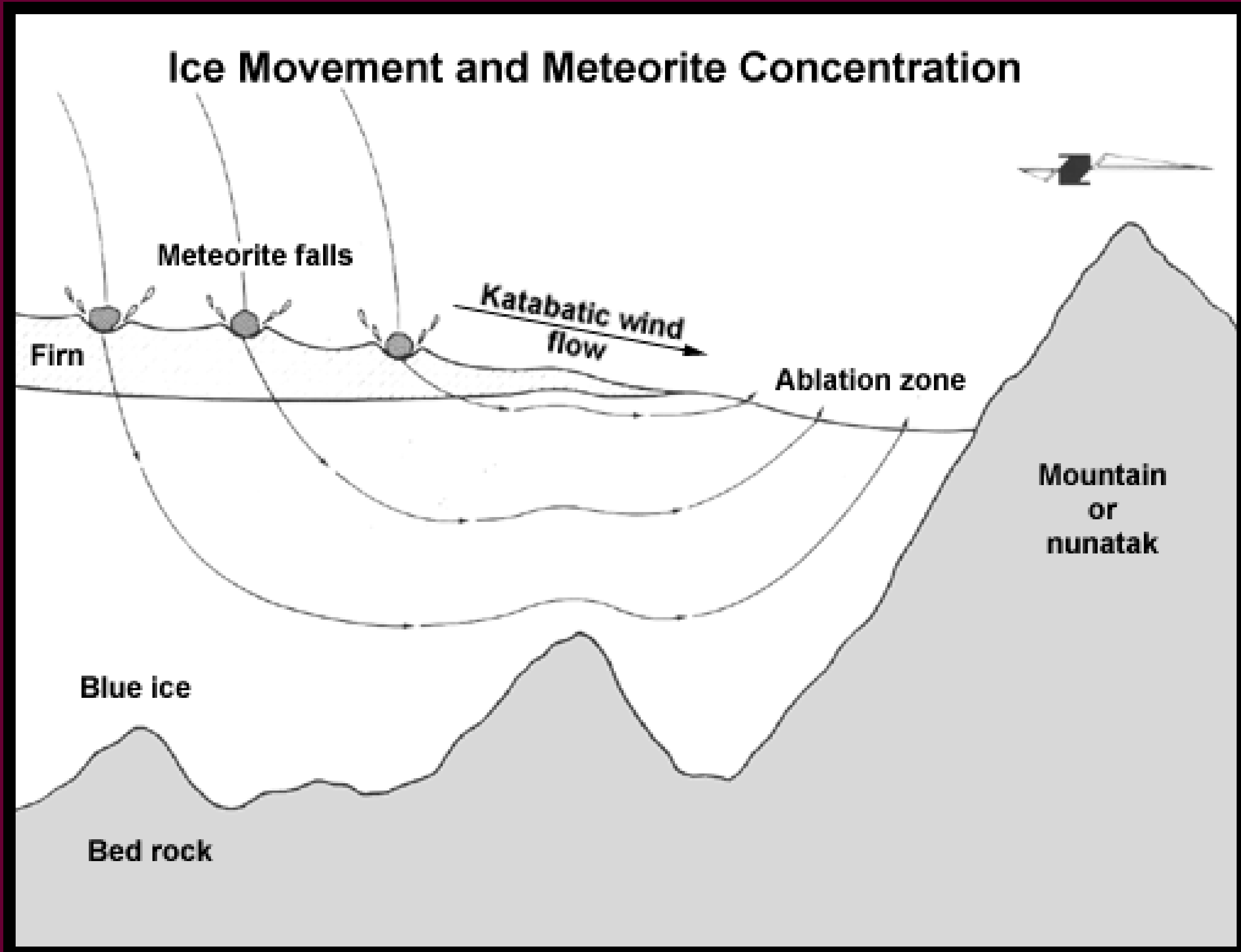
Meteorite type	Fall Percentages
L chondrites	38.0%
H chondrites	34.1%
LL chondrites	7.9%
Irons	4.2%
Eucrites	2.7%
Howardites	2.1%
CM	1.7%
Diogenites	1.2%
Aubrites	1.0%

Where is the best place to find meteorites on Earth?

Where is the best place to find meteorites on Earth?

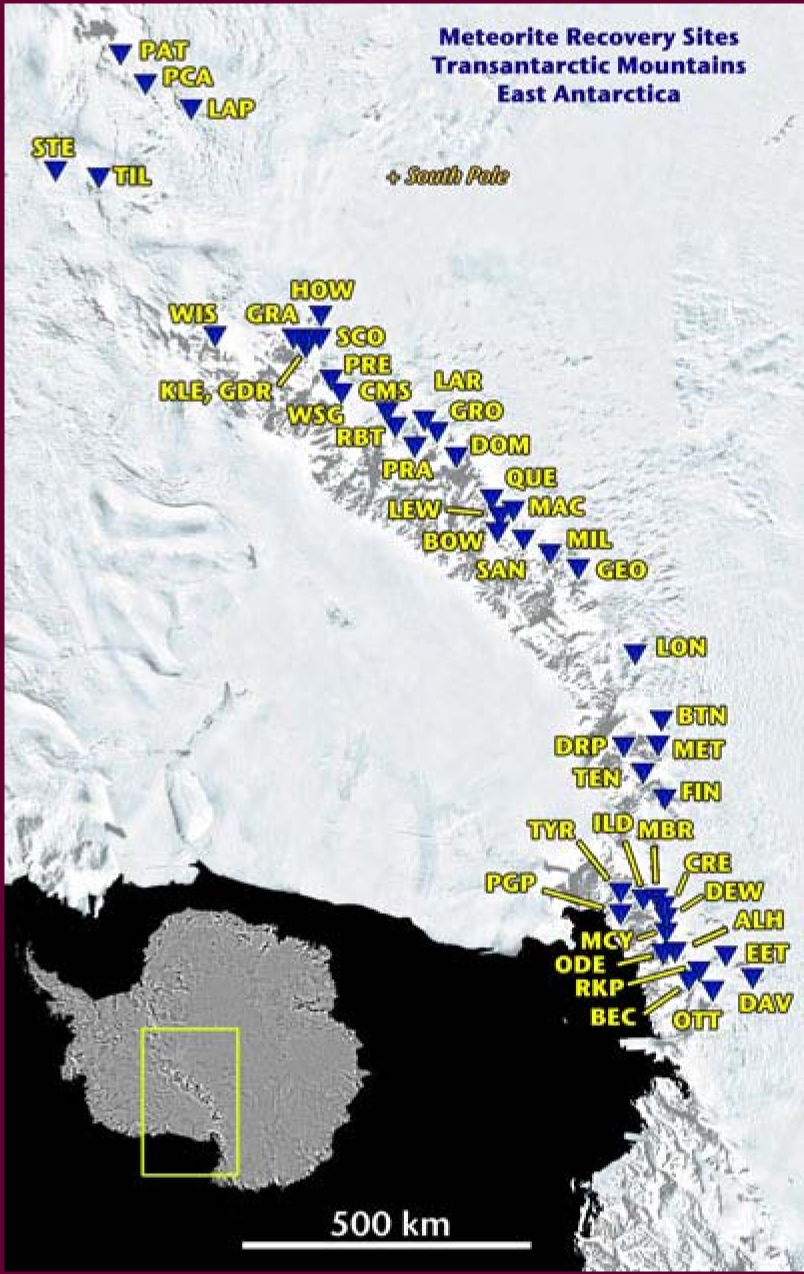
- Antarctica
- Deserts
  - Sahara




Ice Movement and Meteorite Concentration
Meteorite falls
Katabatic wind flow
Firn
Ablation zone
Mountain or nunatak
Blue ice
Bed rock

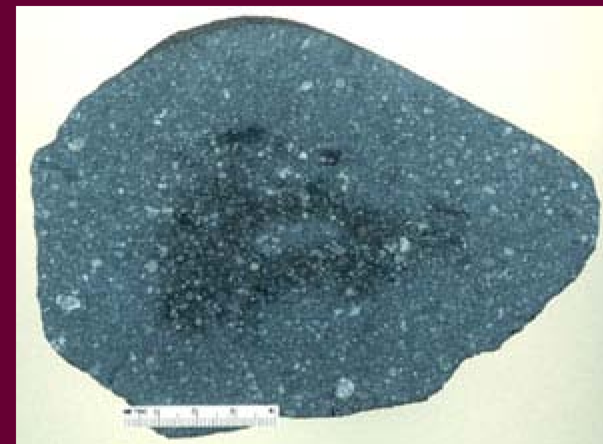
Antarctic Meteorites

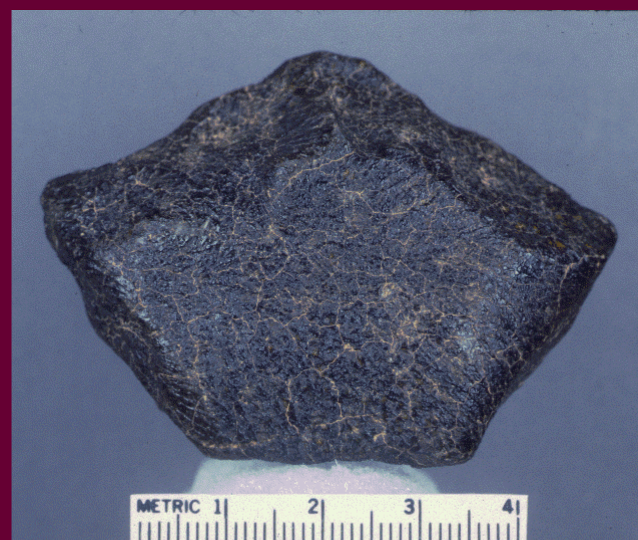
- Designation for which ice field they were found
- ALH Allan Hills
  EET Elephant Moraine
  LEW Lewis Cliff
- Then year and then number (which gives order of discovery)
- For example, ALH 84001 was first meteorite discovered in 1984-1985 field season



How do you know a rock is a meteorite?

- Some possible indicators
- Presence of Iron-Nickel (FeNi) Metal
- Density
- Magnetism
- Presence of Chondrules
- Fusion Crust
- Regmaglypts
  - Ablation of meteorite while passing through atmosphere





Meteor-wrongs

- For example, magnetite (Fe_3O_4) is magnetic, but has grey streak
- The best test is finding

  Ni in the metallic iron

- NWA 736 (H3.7)
- Hassayampa (H4)
- Pultusk (H5)
- NWA 869 (L5)
- Holbrook (L6)
- Long Island (L6)
- NWA 2040 (LL3.5)
- NWA 1584 (LL5)
- NWA 852 (CR2)
- NWA 2086 (CV3)
- NWA 800 (R4)
- NWA 1929 (Howardite)
- NWA 3140 (Ureilite)
- Canyon Diablo (iron)
- Nantan (Iron)
- Sikhote-Alin (Iron)

NWA stands for North West Africa

- Acapulcoites
- Angrites
- Ataxites
- Aubrites
- Brachinites
- CB
- CH
- CI
- CK
- CM
- CO
- CR
- CV
- Diogenites
- EH
- EL
- Eucrites
- H
- Hexahedrites
- Howardites
- L
- LL
- Lodranites
- Mesosiderites
- Octahedrites
- Pallasites
- R
- Ureilites
- Winonaites

Basic types

- Stony – primarily silicates (but can have some FeNi)
- Stony-Iron – ~50-50 mixture of silicates and FeNi
- Iron –almost all FeNi

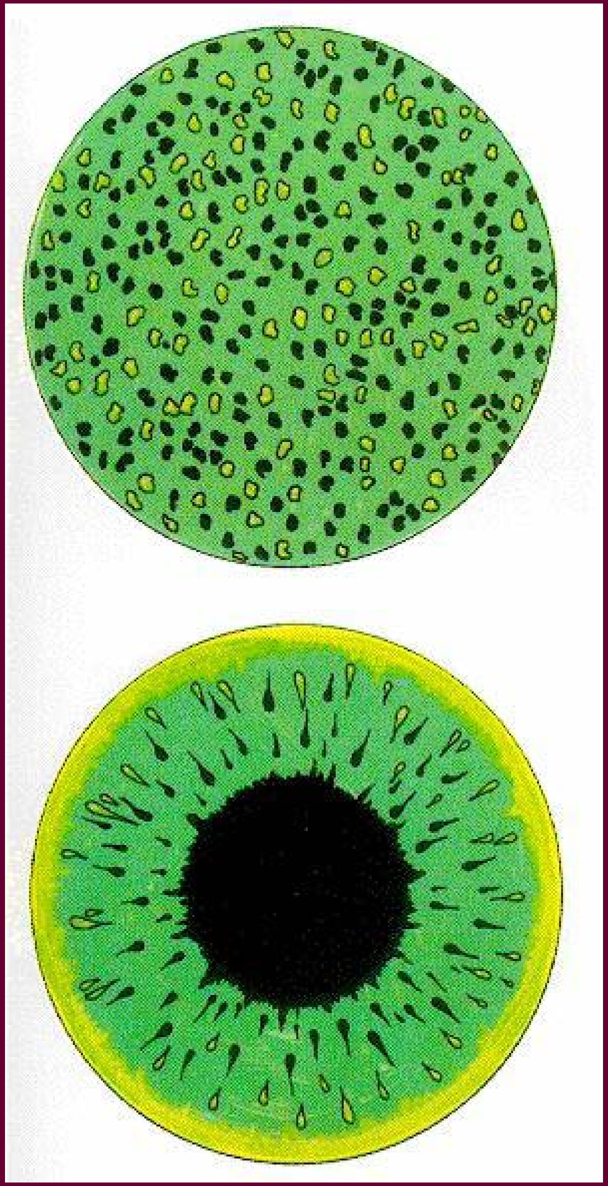
(Silicates are minerals containing Silicon, and usually Oxygen.)

Types of Stony Meteorites

- Chondrites – Heated but have not melted
  - Tend to contain chondrules –frozen molten droplets
  - Aggregates of high- and low-temperature components

- Achondrites – Heating to the point of melting
  - Tend to differentiate
    - Where material segregates due to density

- Chondritic body
- Differentiated body



Ordinary Chondrites

- Most common type of meteorite to fall to Earth
- Ordinary Chondrites – primarily olivine, pyroxene, and metal
  - H – high-iron – 34% of falls
  - L – low-iron – 38% of falls
  - LL – very low-iron – 8% of falls

Carbonaceous Chondrites

- Meteorites that contains high levels of water and organic compounds
- Water is in hydrated silicates
- Have not undergone significant heating (>200°C) since they formed

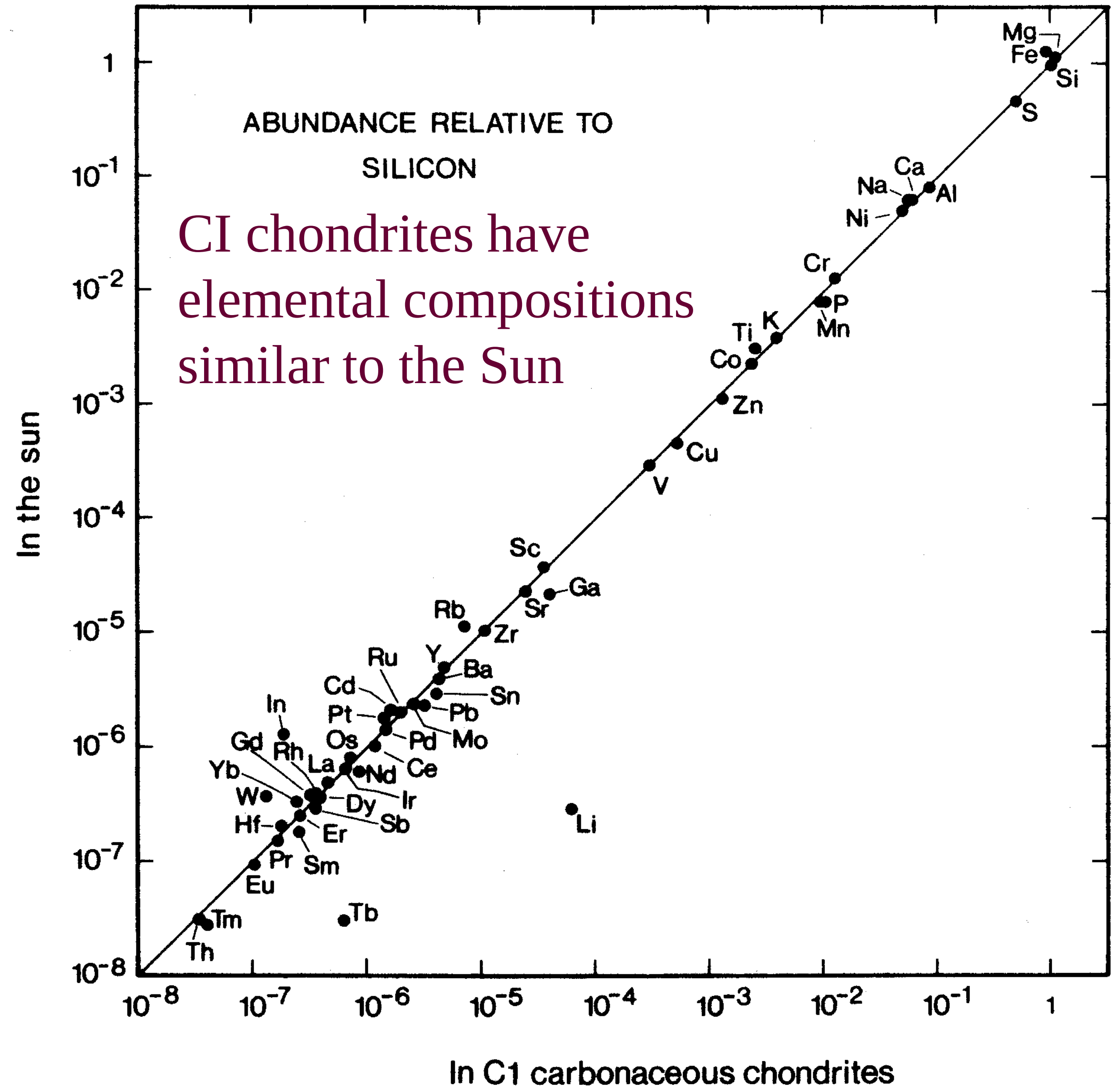
Carbonaceous Chondrites

- CI1 — I is for Ivuna
- CM2 — M is for Mighei
- CR2 — R is for Renazzo
- CH2 — H is for High-Metal
- CB3 — B is for Bencubbin
- CO3 — O is for Ornans
- CV3 — V is for Vigarano
- CK3 — K is for Karoonda
  - Could be CK4 or CK5

CI1 chondrite

- Ivuna – up to 20 wt.% water

CI chondrites have elemental compositions similar to the Sun



CM2 chondrite

- Murchison

CV3 chondrite

- Allende
- Fell February 8, 1969
- Over 2,000 kilograms of material was recovered

CV3 chondrite

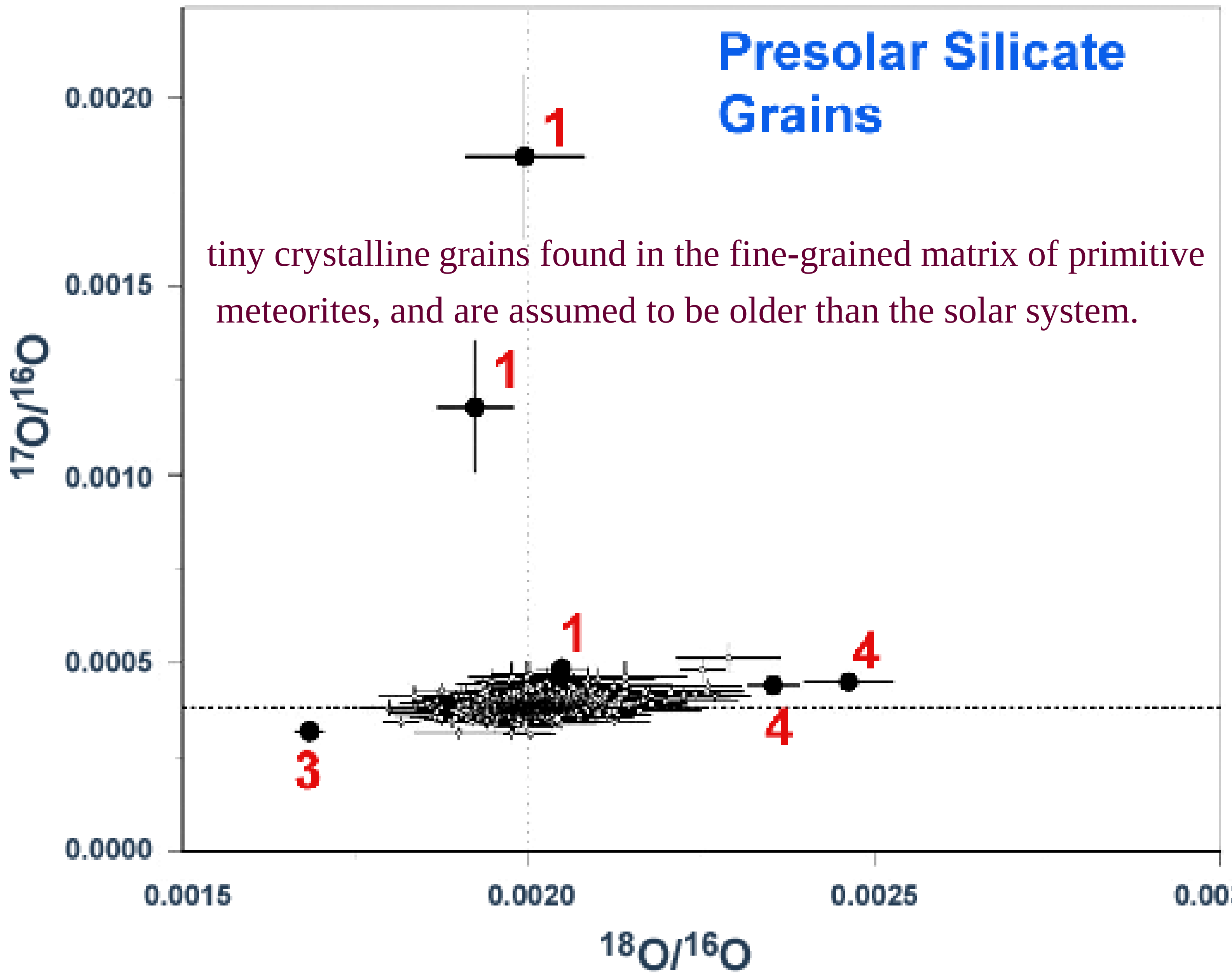
- Contain chondrules
- And Calcium Aluminum Inclusions (CAIs)
  - They consist of high-temperature minerals, including silicates and oxides containing calcium, aluminum, and titanium.
  - Some CAIs were dated at 4.57 billion years, making them the oldest known objects in the solar system

Difference

- Chondrules are round and composed mostly of silicate minerals like olivine and pyroxene
- CAIs are predominantly white to light gray in color and irregularly shaped and rich in refractory minerals like melilite and spinel
- Melilite - $(Ca,Na)_2(Al,Mg)(Si,Al)_2O_7$
- Spinel - $MgAl_2O_4$

Other types of chondrites

- Enstatite Chondrites (EH and EL) – primarily enstatite (Magnesium silicate)
- R chondrites –primarily olivine, no FeNi



tiny crystalline grains found in the fine-grained matrix of primitive meteorites, and are assumed to be older than the solar system.

(From Messenger *et al.*, 2003, *Science*, v. 300, p. 105-108.)

Achondrites

- Stony meteorites that were heated to the point of melting
  - HEDs – basaltic crust (lava flows)
  - Eucrites - pigeonite and plagioclase
  - Howardites - mixtures of eucrite and diogenite material
  - Diogenites - orthopyroxene
- HEDs are thought to be fragments of asteroid 4 Vesta

Eucrites

- Basalts
- Contain pigeonite and plagioclase

Diogenites

- mainly magnesium-rich orthopyroxene
- Minor plagioclase
- Sometimes olivine

Howardites

- Mixture of eucritic and diogenitic material

Aubrites

- Enstatite-rich achondrite

Angrites

– contain predominately anorthite, Al-Ti diopside-hedenbergite, and Ca-rich olivine

Irons

- FeNi
- Some show the growth of two FeNi minerals with different crystal structures
- Widmanstätten pattern – shows when etched with weak acid
- Kamacite – light – Ni-poor
- Taenite – dark – Ni-rich
- Most thought to be cores of differentiated bodies

Widmanstätten pattern

- **Widmanstätten patterns** are composed of interleaving kamacite and taenite bands (or ribbons) called *lamellae*.

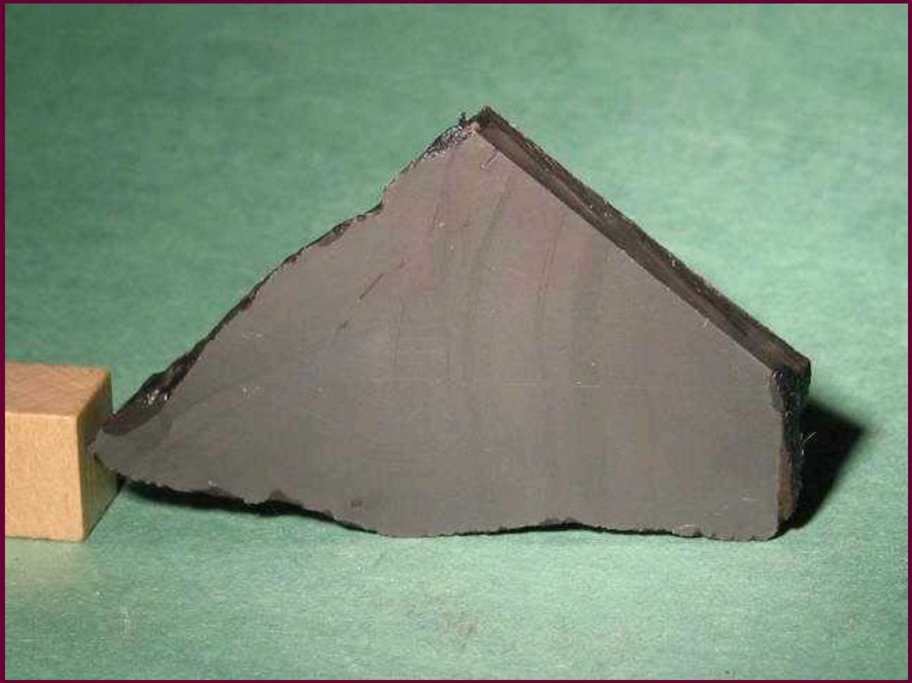
- Kamacite - metallic iron with up to 7.5% nickel
- Taenite - iron with 20-65% nickel

Irons

- Ataxite – made almost entirely of taenite (more than 16% Ni)
- Octahedrite – composed of both taenite and kamacite (6-16% Ni)
- Hexahedrite - composed almost entirely of kamacite (less than 6% Ni)

Ataxite

- Made almost entirely of taenite



Octahedrite

- Have Widmanstätten pattern
- Plessite are the spaces between larger kamacite and taenite plates are often filled by a fine-grained mixture of kamacite and taenite

Hexahedrite

- Often have fine parallel line called Neumann lines
- Shock-induced, structural deformation of the kamacite

Stony-Irons

- Pallasites
- Mesosiderites

Pallasite

- Olivine and FeNi

Any Questions?