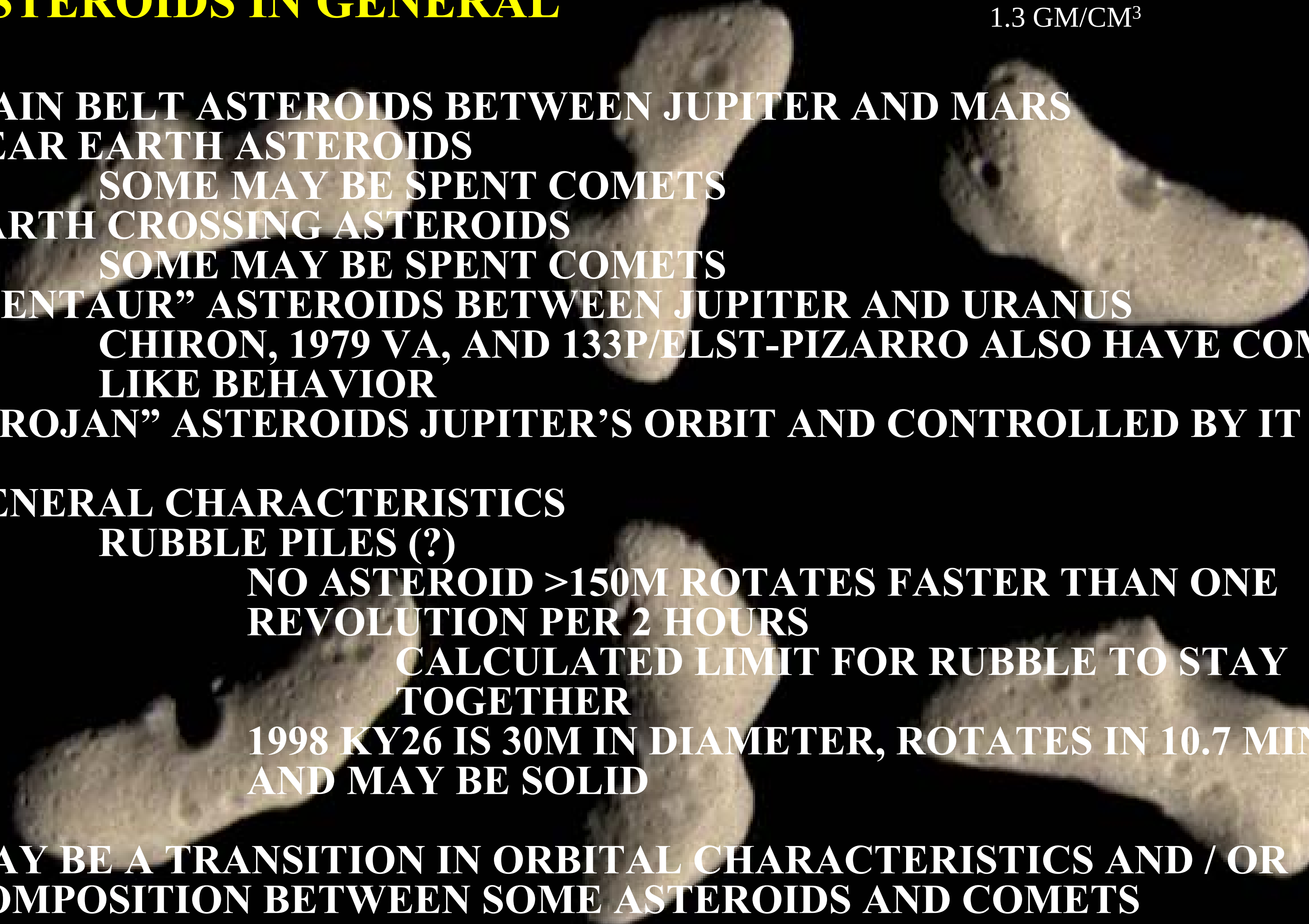
ASTEROIDS AND COMETS: POTENTIAL RESOURCES

LECTURE 21 NEEP 533

HARRISON H. SCHMITT

ASTEROIDS IN GENERAL



EROS C-TYPE
NASA/NEAR SHOEMAKER/APL
11X11X34 KM
1.3 GM/CM^3

MAIN BELT ASTEROIDS BETWEEN JUPITER AND MARS
NEAR EARTH ASTEROIDS
- SOME MAY BE SPENT COMETS

EARTH CROSSING ASTEROIDS
- SOME MAY BE SPENT COMETS

“CENTAUR” ASTEROIDS BETWEEN JUPITER AND URANUS
- CHIRON, 1979 VA, AND 133P/ELST-PIZARRO ALSO HAVE COMET-LIKE BEHAVIOR

“TROJAN” ASTEROIDS JUPITER’S ORBIT AND CONTROLLED BY IT

GENERAL CHARACTERISTICS
- RUBBLE PILES (?)
  - NO ASTEROID >150M ROTATES FASTER THAN ONE REVOLUTION PER 2 HOURS
    - CALCULATED LIMIT FOR RUBBLE TO STAY TOGETHER
  - 1998 KY26 IS 30M IN DIAMETER, ROTATES IN 10.7 MIN. AND MAY BE SOLID

MAY BE A TRANSITION IN ORBITAL CHARACTERISTICS AND / OR COMPOSITION BETWEEN SOME ASTEROIDS AND COMETS

OTHER ASTEROIDS

- S-TYPE
  - INNER ASTEROID BELT
  - EVIDENCE OF HEATING AND DIFFERENTIATION
  - 29 TELESCOPIC SPECTRA (Binzel, et al., 1996)
    - INTERMEDIATE BETWEEN S-TYPE AND ORDINARY CHONDRITES
      - 1. DISTINCT ROCK TYPES VS DIVERSE LARGER BODIES
      - 2. ABUNDANCE OF OPAQUE MATERIALS
      - 3. FRESH SURFACES (MOST LIKELY)
- BASALTIC ACHONDRITES (6%)
  - 4 VESTA AT 2.36 AU [MAIN BELT PARENT (?)]
  - TOUTATIS - NEA (RADAR STUDY)
    - 4.5X2.4X1.9KM, 2.1 GM/CM3, TWO ROTATIONS, I.E., TUMBLING (5.4 AND 7.3 DAYS)
  - 1459 MAGNYA AT 3.15 AU [FRAGMENT OF LARGER BODY (?)]
    - (Lazzaro, et al, 2000, Science, 288)

EROS
C-TYPE (REVISED BY GRS DATA)
11X11X33 KM
2.7 GM/CM^3
5.27 HR ROTATION
NASA/NEAR SHOEMAKER/APL

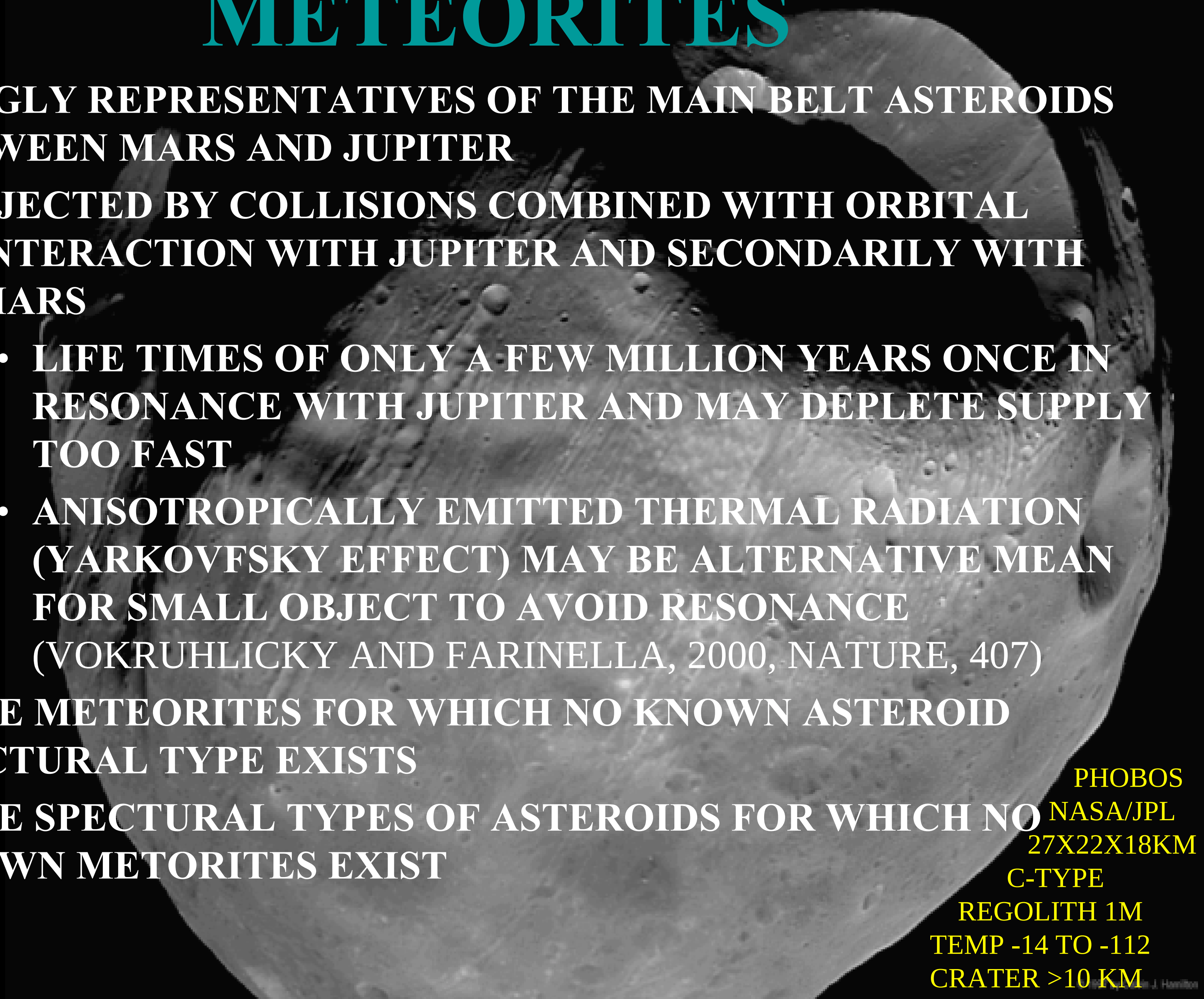
OTHER ASTEROIDS

- D-TYPE CARBONACEOUS CHONDRITE (BEYOND MAIN BELT ASTEROIDS)
  - TAGISH LAKE METEORITE (HIROI, ET AL, 2001, SCIENCE, 293)
    - 4-5% CARBON (MOST KNOWN)
    - PRESOLAR GRAINS
    - CARBONATE MINERALS
- M-TYPE (MAIN BELT)
  - 16 PSYCHE
    - RADAR SUGGESTS METAL
  - KLEOPATRA (Ostro, et al, 2000, Science, 288)
    - RADAR: 217X94X81 KM, DUMBELL SHAPE, 3.5 GM/CM3 REGOLITH

243 IDA (56 KM LONG) AND
ITS MOON, DACTYL (1.5 KM)
NASA/GALILEO/JPL

METEORITES

- **LARGLY REPRESENTATIVES OF THE MAIN BELT ASTEROIDS BETWEEN MARS AND JUPITER**
  - **EJECTED BY COLLISIONS COMBINED WITH ORBITAL INTERACTION WITH JUPITER AND SECONDARILY WITH MARS**
    - **LIFE TIMES OF ONLY A FEW MILLION YEARS ONCE IN RESONANCE WITH JUPITER AND MAY DEPLETE SUPPLY TOO FAST**
    - **ANISOTROPICALLY EMITTED THERMAL RADIATION (YARKOVFSKY EFFECT) MAY BE ALTERNATIVE MEAN FOR SMALL OBJECT TO AVOID RESONANCE** (VOKRUHLICKY AND FARINELLA, 2000, NATURE, 407)
- **SOME METEORITES FOR WHICH NO KNOWN ASTEROID SPECTURAL TYPE EXISTS**
- **SOME SPECTURAL TYPES OF ASTEROIDS FOR WHICH NO KNOWN METORITES EXIST**



PHOBOS
NASA/JPL
27X22X18KM
C-TYPE
REGOLITH 1M
TEMP -14 TO -112
CRATER >10 KM

METORITE CHARACTERISTICS

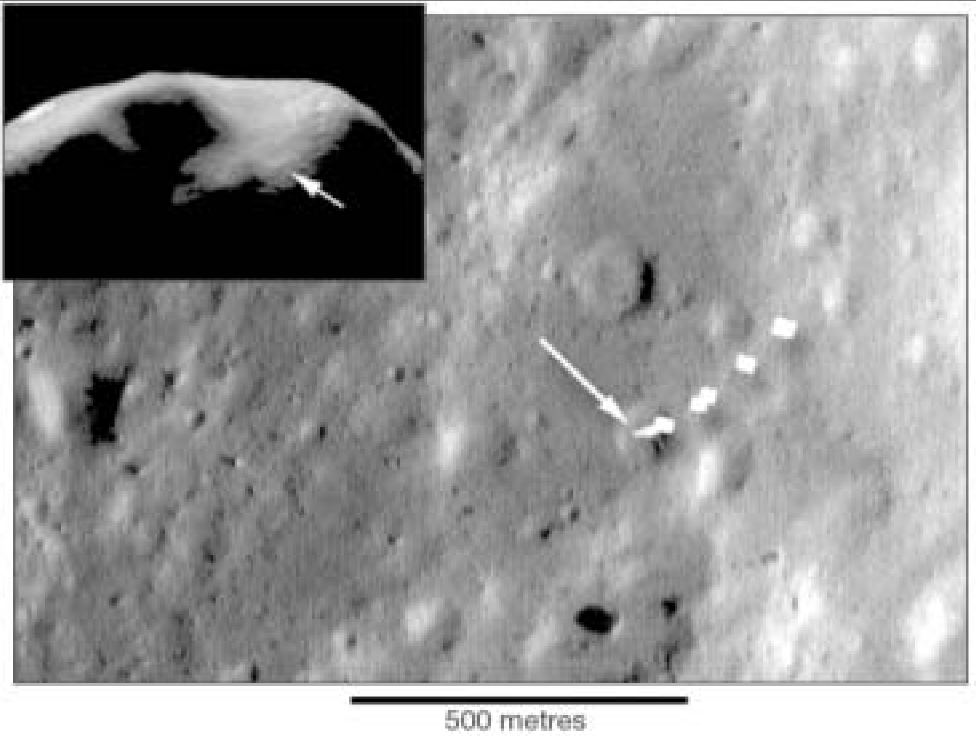
- **STONY-IRONS (1% OF ALL FALLS)**
- **ABOUT 50% FERROUS METAL ALLOYS, 50% SILICATES**
    - **APPARENTLY RELATED TO HIGH PRESSURE CRYSTALLIZATION IN MANTLE OF A NOW DISINTEGRATED PLANET.**

243 IDA
NASA/JPL
19X52 KM

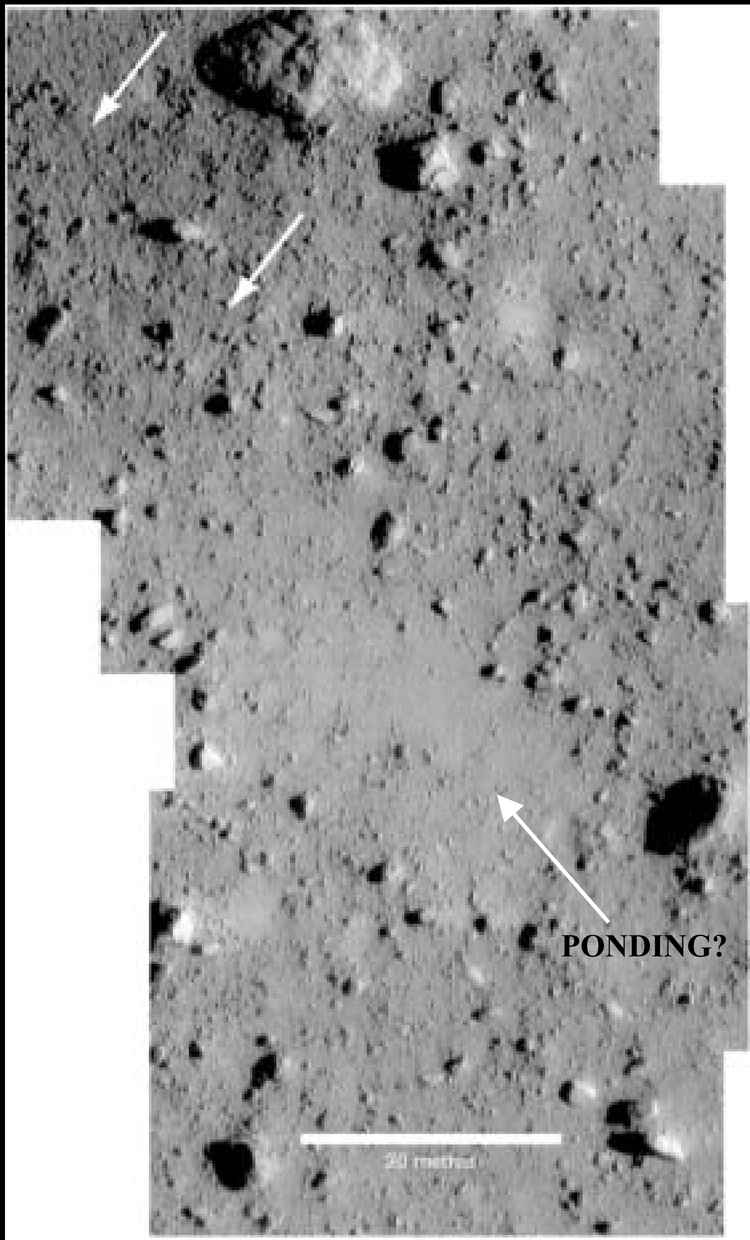
- **IRONS (3% OF ALL FALLS)**
- **ABOUT 99% METALLIC FE-NI-CO ALLOYS**
    - **INCLUSIONS OF FES, PHOSPHIDES, CARBIDES, GRAPHITE, DIAMONDS, SILICATES**
    - **APPARENTLY RELATED TO HIGH PRESSURE CRYSTALLIZATION, SUCH AS IN THE CORE OF A NOW DISINTEGRATED PLANET.**

EROS
FINAL DESCENT

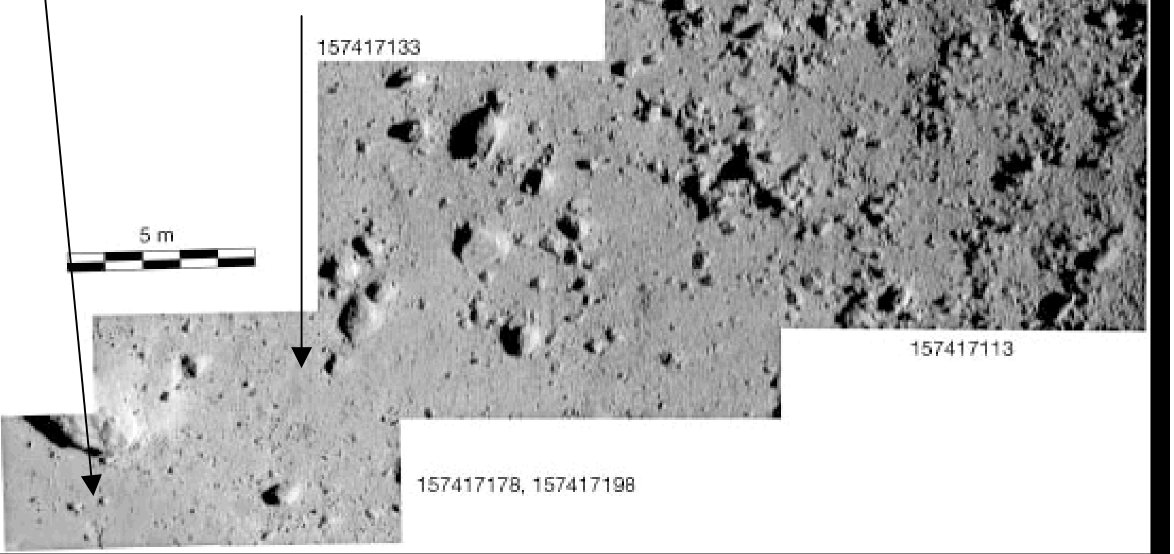
NASA/NEAR SHOEMAKER/APL



GROVES



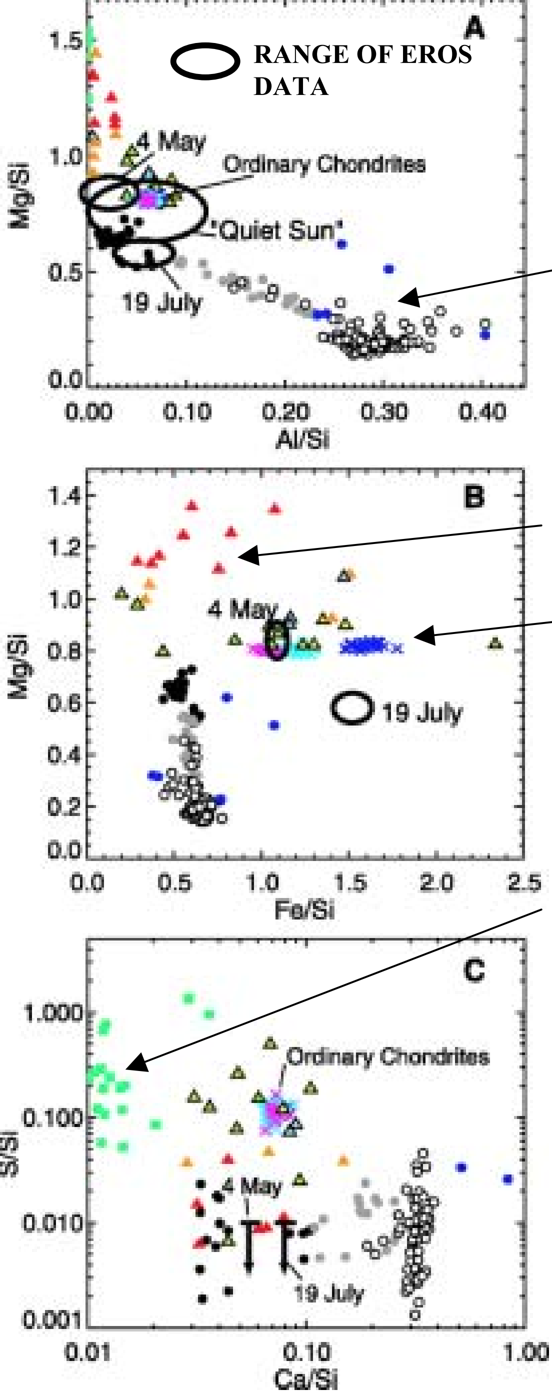
NOTE DEPRESSIONS, I.E., SUSIDENCE FEATURES



EROS
GAMMA RAY SPECTROMETER DATA

(UPPER ~ 10 CM OF MATERIAL)

TROMBKA, ET AL, 2000, SCIENCE, 289; TROMBKA, ET AL, 2000, SCIENCE)

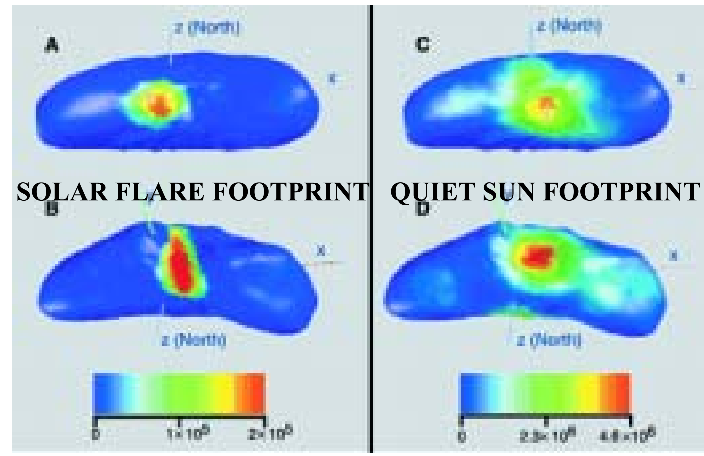


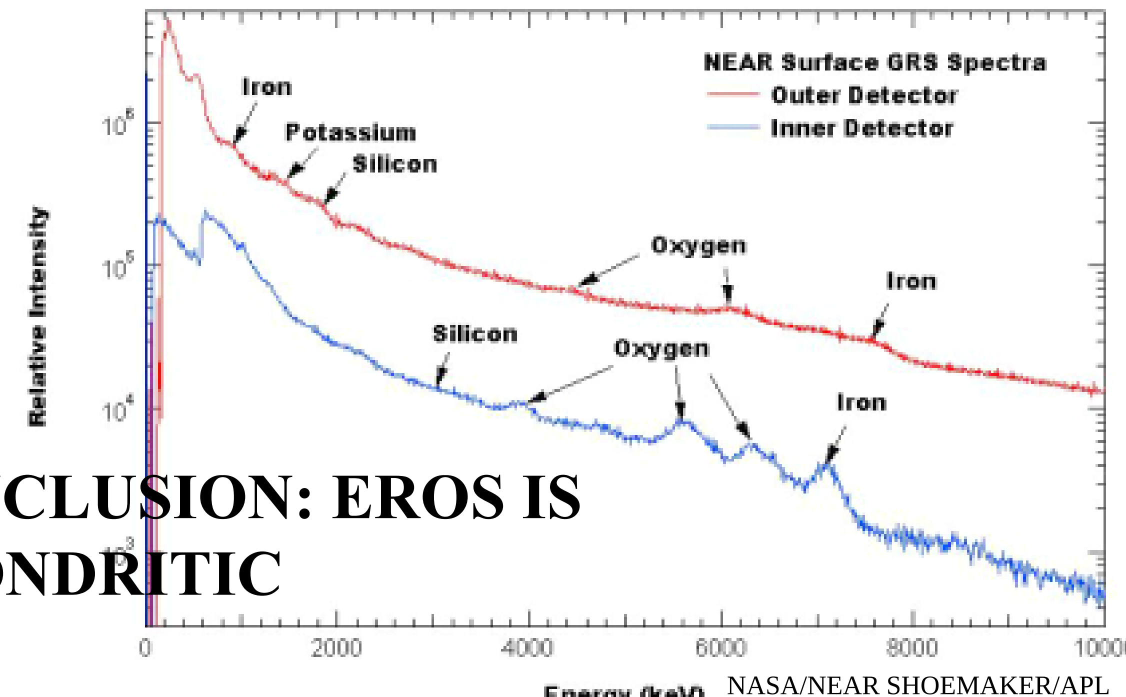
ACHONDRITES (CIRCLES)

PRIMATIVE ACHONDRITES (TRIANGLES)

CHONDRITES (CROSSES)

PALLASITES (SQUARES)





CONCLUSION: EROS IS CHONDRITIC

NASA/NEAR SHOEMAKER/APL

SPACE WEATHERING

(TENDS TO GIVE A RED TINT TO THE SURFACES OF MOST ASTEROIDS)

WEATHERING FACTORS:

MICROMETEORS (PRODUCE NANO-PHASE IRON)

SOLAR WIND/SOLAR FLARE IONS

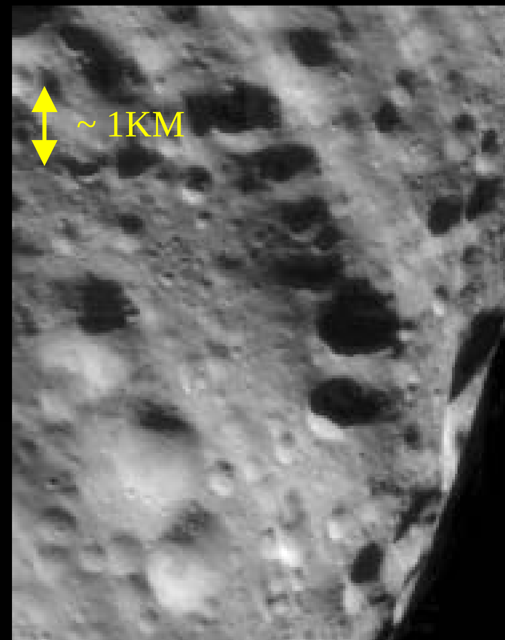
GALACTIC COSMIC RAYS

COLD / HEAT

EROS

CLOSE-UPS AND COLOR

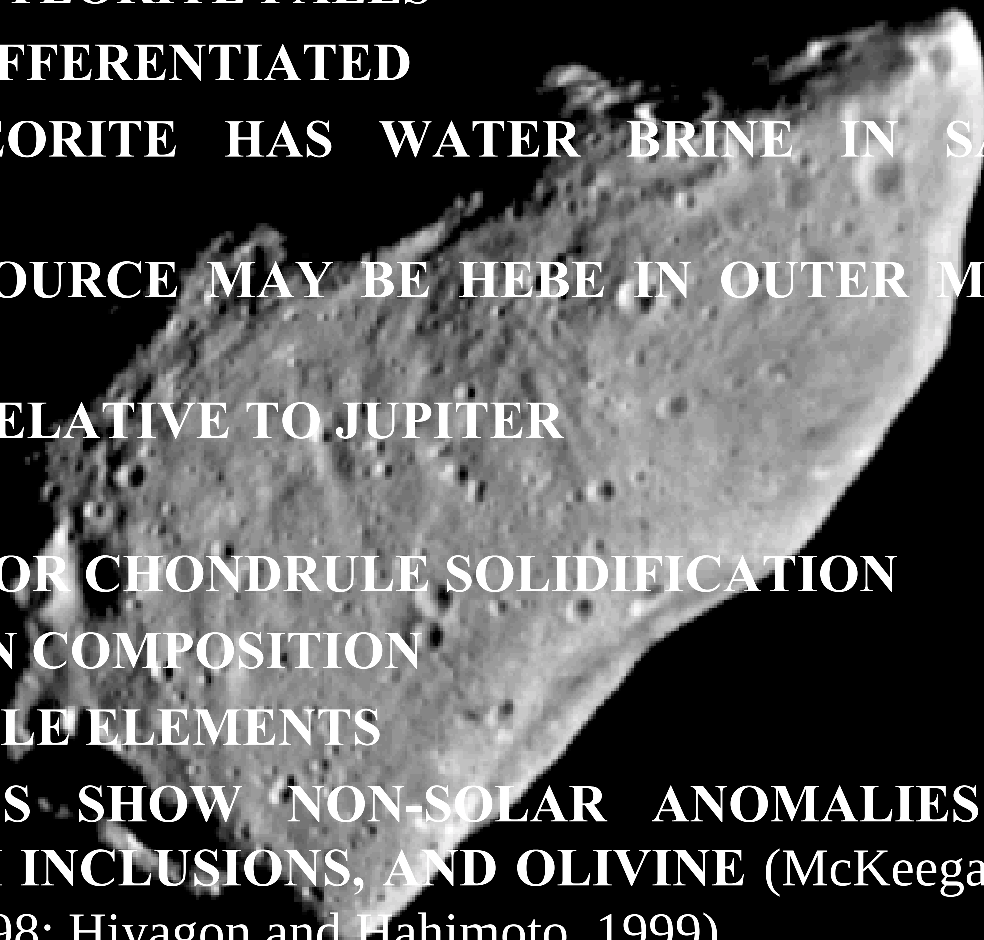
NASA/NEAR SHOEMAKER/APL



CHONDRITES

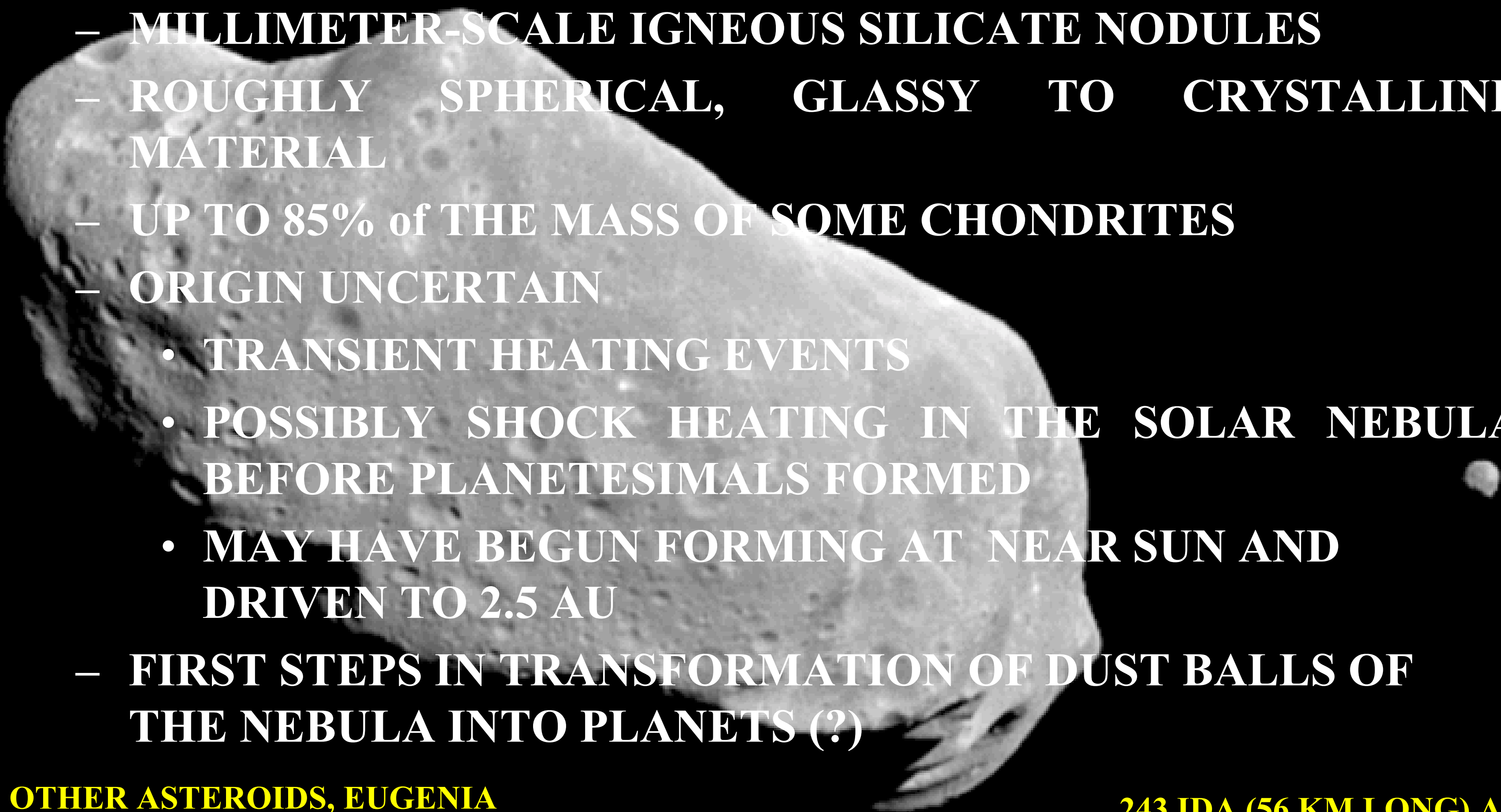
C-TYPE ASTEROIDS

- **80% OF OBSERVED METEORITE FALLS**
- **SILICATE-RICH / UNDIFFERENTIATED**
  - **MONAHANS METEORITE HAS WATER BRINE IN SALT CRYSTALS**
- **SPECTRA SUGGEST SOURCE MAY BE HEBE IN OUTER MAIN BELT**
  - **RIGHT POSITION RELATIVE TO JUPITER**
- **4.567 B.Y. OLD**
  - **10^7 YEAR SPREAD FOR CHONDRULE SOLIDIFICATION**
- **RESEMBLE THE SUN IN COMPOSITION**
  - **EXCEPT IN VOLATILE ELEMENTS**
  - **OXYGEN ISOTOPES SHOW NON-SOLAR ANOMALIES IN SPINEL, Ca-Al-RICH INCLUSIONS, AND OLIVINE** (McKeegan, et al, 1998; Choi, et al, 1998; Hiyagon and Hahimoto, 1999)
- **REMNANT MAGNETISM INDICATES FIELD OF 1-10 G**
- **HIGH PRESSURE SHOCK ASSEMBLAGES IN VEINS**



951 GASPRA 19X12/11 KM
7 HR ROTATION PERIOD
NASA/GALILEO/JPL

CHONDRITES -2



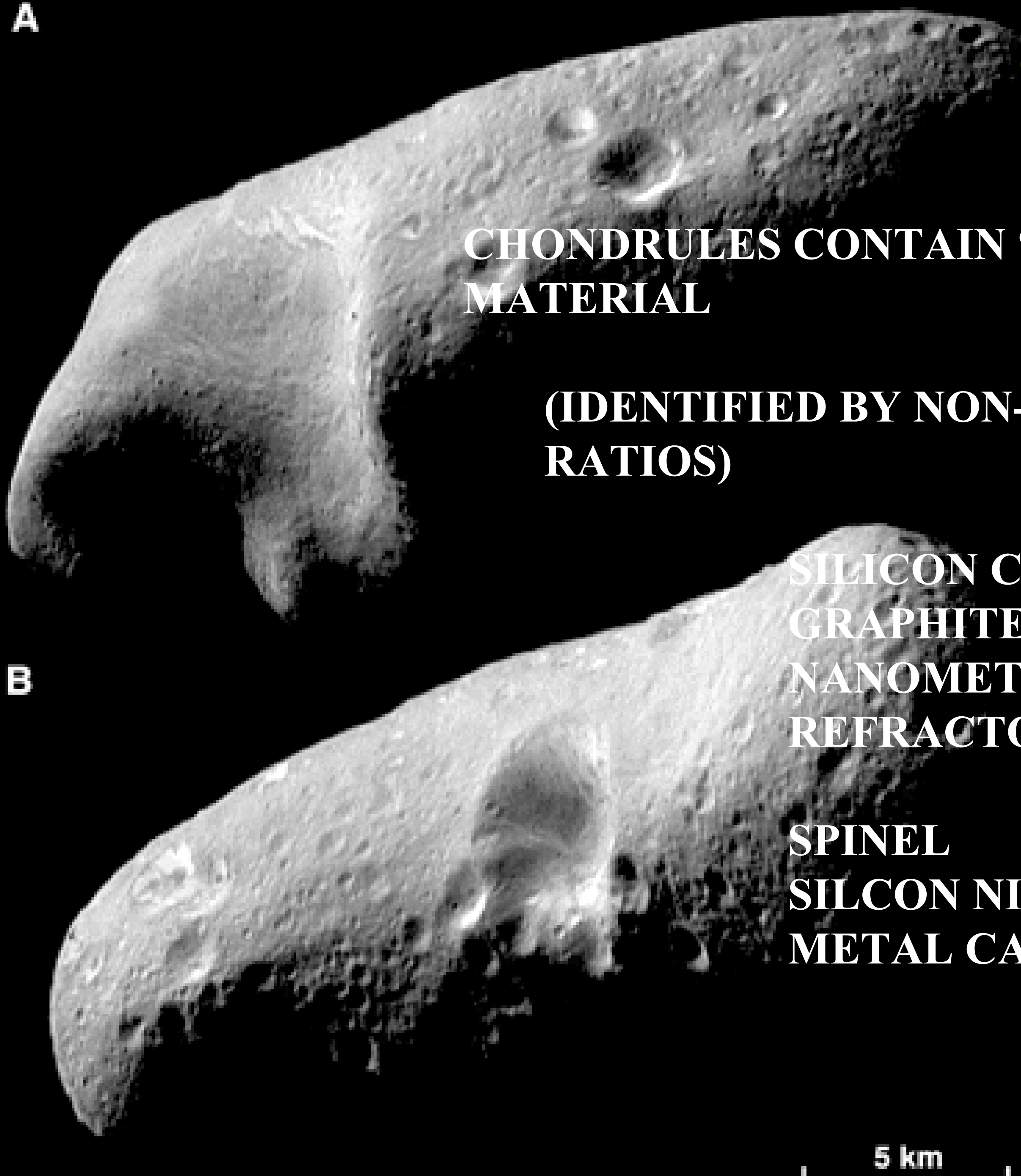
- CONTAIN "CHONDRULES" RICH IN CA AND AL
  - MILLIMETER-SCALE IGNEOUS SILICATE NODULES
  - ROUGHLY SPHERICAL, GLASSY TO CRYSTALLINE MATERIAL
  - UP TO 85% of THE MASS OF SOME CHONDRITES
  - ORIGIN UNCERTAIN
    - TRANSIENT HEATING EVENTS
    - POSSIBLY SHOCK HEATING IN THE SOLAR NEBULA BEFORE PLANETESIMALS FORMED
    - MAY HAVE BEGUN FORMING AT NEAR SUN AND DRIVEN TO 2.5 AU
  - FIRST STEPS IN TRANSFORMATION OF DUST BALLS OF THE NEBULA INTO PLANETS (?)

TWO OTHER ASTEROIDS, EUGENIA AND ANTIOPE, AREKNOWN TO HAVE MOONS. 120 KM ANTIOPE CONSISTS OF TWO, EQUAL SIZED BODIES, SEPARATED BY 170KM.

243 IDA (56 KM LONG) AND ITS MOON, DACTYL (1.5 KM)
S-TYPE
2.6 GM/CM³

NASA/GALILEO/JPL

CHONDRITES -3



CHONDRULES CONTAIN "PRE-SOLAR" MATERIAL

(IDENTIFIED BY NON-SOLAR ISOTOPIC RATIOS)

SILICON CARBIDE
GRAPHITE
NANOMETER-SIZED DIAMONDS
REFRACTORY (Al_2O_3) OXIDES

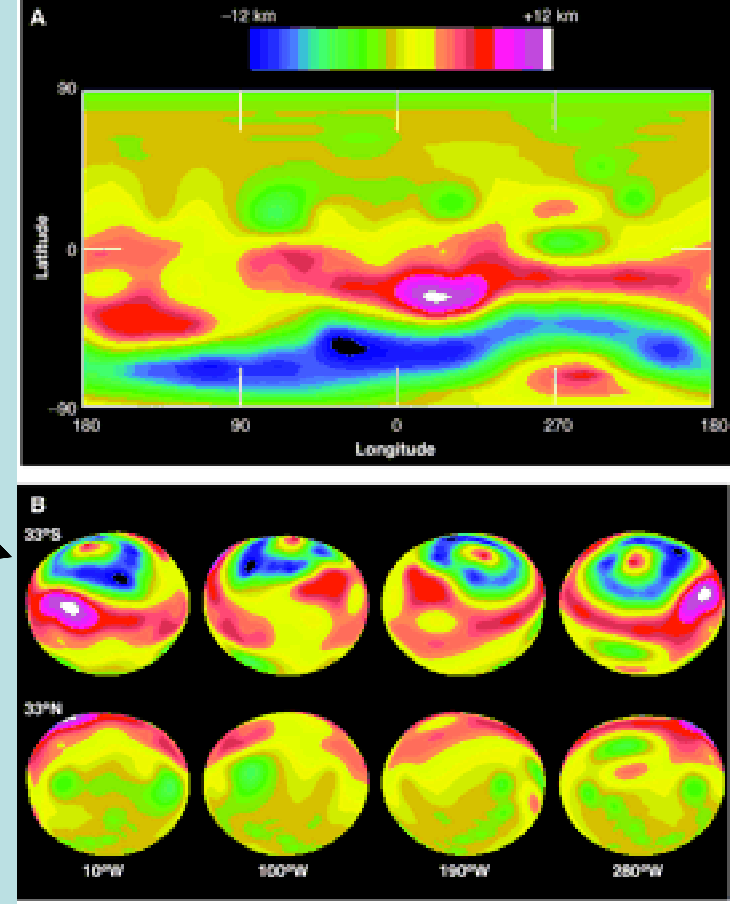
SPINEL
SILCON NITRIDE
METAL CARBIDES

EROS MOSAICS
VEVERKA, ET AL, 2000, SCIENCE, 289
NASA/NEAR SHOEMAKER/ARL

VESTA

BASALTIC A-CHONDRITE (?)
MEAN DIA 530KM

460 KM DIAMETER CRATER,
13 KM DEEP
MAPPED USING SPECTRAL PROPERTIES



CRATERING ON ASTEROIDS (Veverka, et al, 1997)

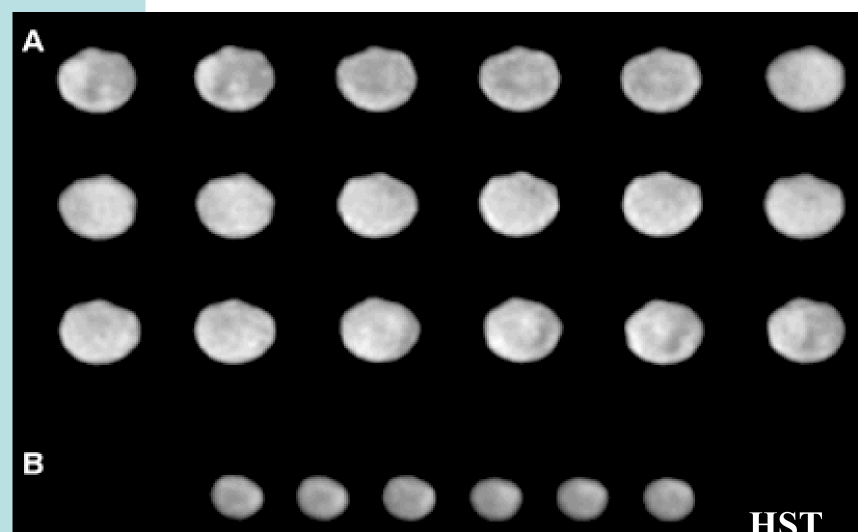
CRATERS FORM WITH DIAMETERS COMPARABLE TO ASTEROIDS MEAN RADIUS

IMPACT DOES NOT BREAK UP BODY AT THIS SIZE

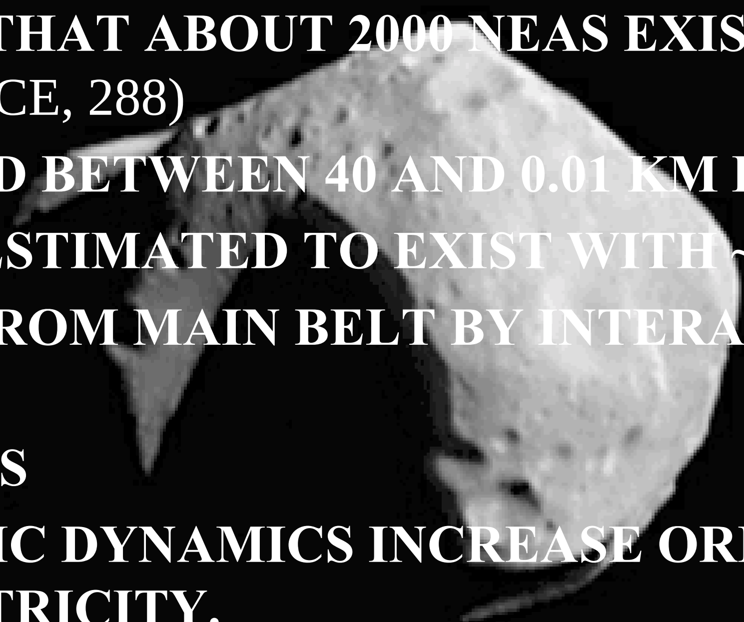
CRATER SIZE-FREQUENCY DISTRIBUTION SIMILAR TO THAT ON THE MOON

LARGE CRATERS HAVE NOT DISTROYED EACH OTHER

PROBABLY DUE TO ACCELERATION OF EJECTA TO ESCAPE VELOCITY



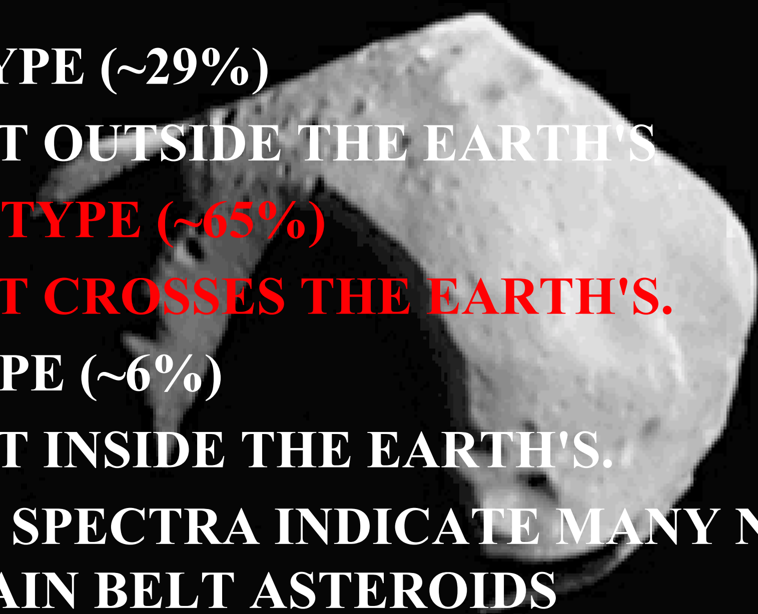
NEAR EARTH ASTEROIDS



- **ESTIMATES ARE THAT ABOUT 2000 NEAS EXIST** (SEE BOTTKE, ET AL, 2000, SCIENCE, 288)
  - **~950 DETECTED BETWEEN 40 AND 0.01 KM DIAMETER**
  - **~900 OTHERS ESTIMATED TO EXIST WITH ~1 KM DIAMETER**
    - **EJECTED FROM MAIN BELT BY INTERACTIONS WITH JUPITER.**
    - **COLLISIONS**
      - **CHAOTIC DYNAMICS INCREASE ORBITAL ECCENTRICITY.**
    - **RELATIVELY SHORT (10-100 MYR) LIFE-TIMES AND THUS MUST BE REPLENISHED RAPIDLY COMPARED TO THE AGE OF THE SOLAR SYSTEM.**

MATHILDE 59X47 KM
ALBEDO 3-4%
17.4DAY ROTATION
DENSITY 1.3
C TYPE
NASA/NEAR/APL

NEAR EARTH ASTEROIDS



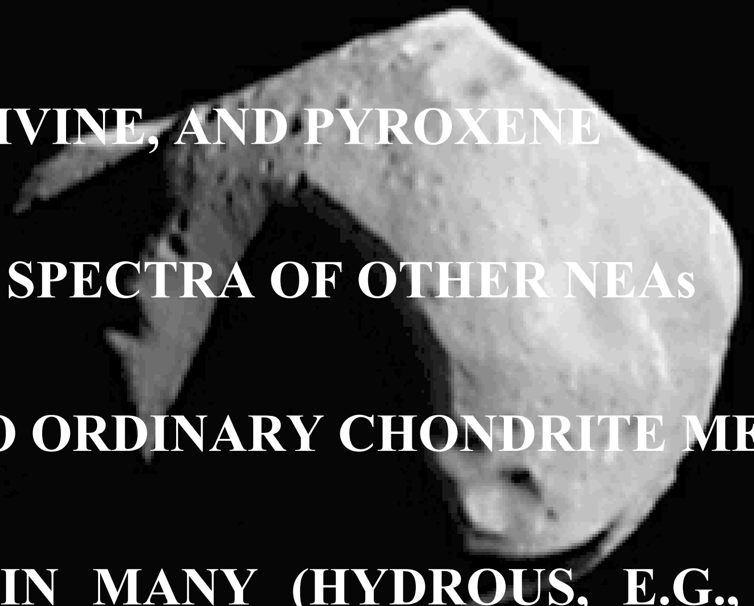
- AMOR TYPE (~29%)
  - ORBIT OUTSIDE THE EARTH'S
- APOLLO TYPE (~65%)
  - ORBIT CROSSES THE EARTH'S.
- ATEN TYPE (~6%)
  - ORBIT INSIDE THE EARTH'S.

- REFLECTANCE SPECTRA INDICATE MANY NEAS ARE SIMILAR TO MAIN BELT ASTEROIDS
- OTHERS APPEAR TO BE EXTINCT COMET NUCLEI
  - SURFACE VOLATILES DEPLETED
  - INERT CRUST SEALS REMAINING VOLATILES INSIDE

MATHILDE 59X47 KM
ALBEDO 3-4%
17.4DAY ROTATION
DENSITY 1.3
C TYPE
NASA/NEAR/APL

NEAR EARTH ASTEROIDS

- **SPECTRA OF NEA 1862 APOLLO**
  - **METAL, OLIVINE, AND PYROXENE**
- **6 TELESCOPIC SPECTRA OF OTHER NEAs**
  - **SIMILAR TO ORDINARY CHONDRITE METEORITE SPECTA**
- **ALTERATION IN MANY (HYDROUS, E.G., CLAYS AND IRON OXIDES)**
  - **BOTH PRE-DATED AND POST-DATED ACCRETION OF PARENT BODY**



MATHILDE 59X47 KM
C-TYPE
ALBEDO 4% (6X<EROS)
1.3 GM/CM^3
NASA/NEAR/APL

ASTEROID RESOURCES

- MAJOR TYPES
  - SILICATE DOMINATED REGOLITH
    - SORTED BY SIZE AND OR DENSITY
    - UNSORTED
  - METAL DOMINATED REGOLITH
  - SILICATE / METAL MIXED REGOLITH
    - SORTED
    - UNSORTED

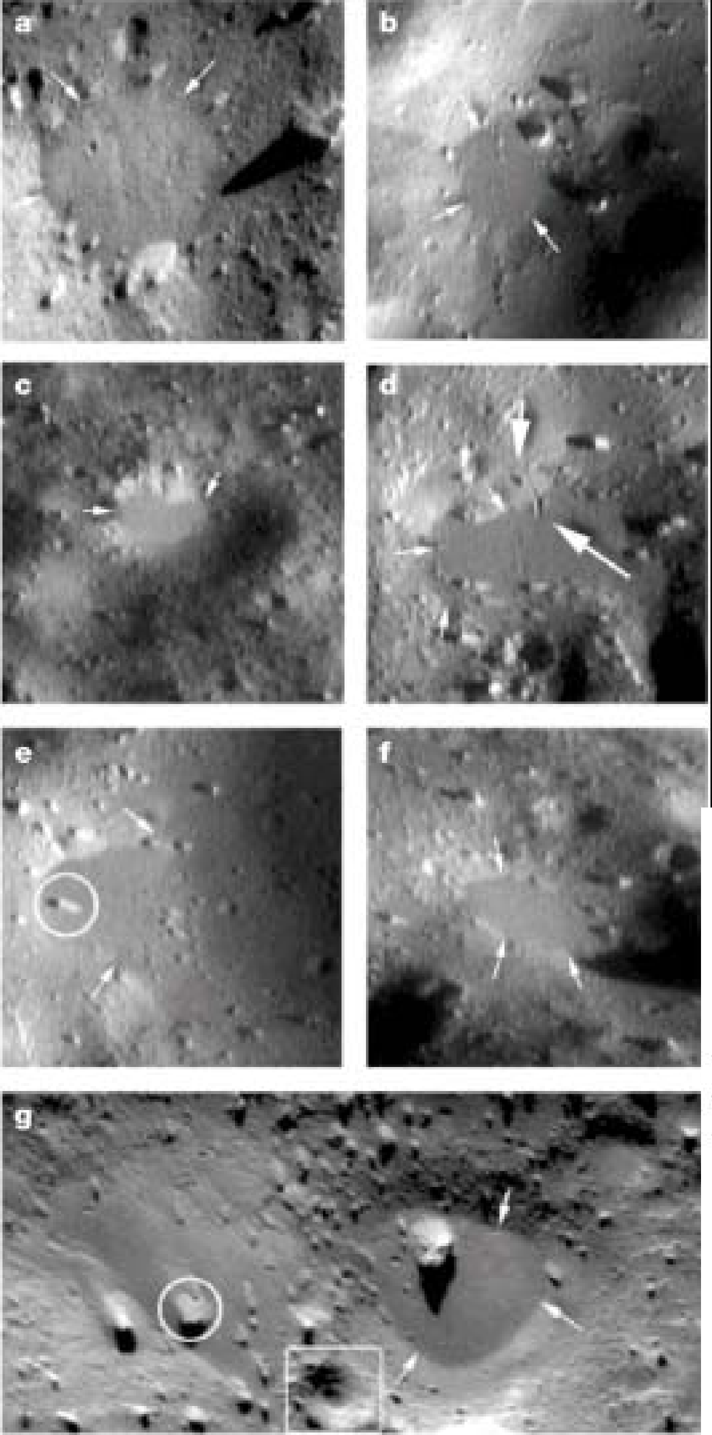
DEIMOS
NASA/JPL
15X12X11 KM
C-TYPE

SILICATE DOMINATED REGOLITH


EROS CLOSE-UP
NASA/APL

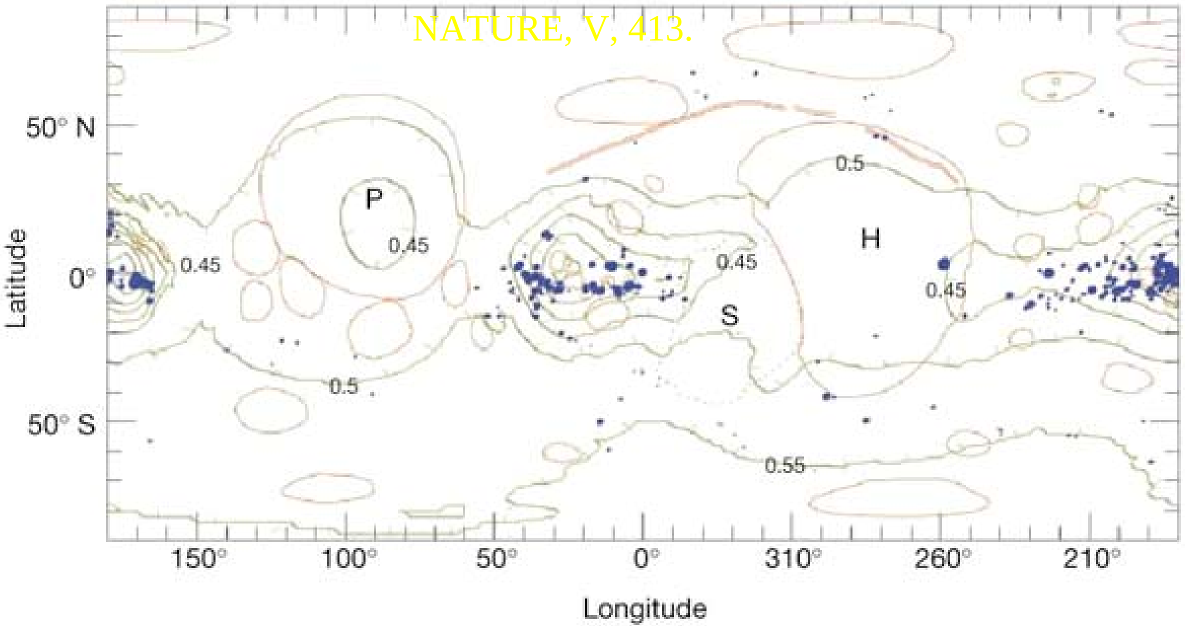
- **CHONDRITES (C-TYPE) AND ACHONDRITES**
  - **UNSORTED REGOLITH VERY SIMILAR TO THE MOON'S REGOLITH**
    - **SOLAR WIND VOLATILES**
    - **SOLAR WIND DERIVED VOLATILES**
    - **HYDROUS MINERALS**
    - **RADIATION PROTECTION MATERIALS**
- **EXAMPLES:**
  - **EROS [NEAR-EARTH, C-TYPE ASTEROID]** (NEAR-SHOEMAKER REFERENCES, E.G., SCIENCE, 2000, 289)
    - **LOW DENSITY REGOLITH**
    - **FINE GRAINED REGOLITH LOCALLY PONDED**
  - **MATHILDE [NEAR-EARTH, C-TYPE ASTEROID]**
    - **MAY BE CARBON-RICH [LOW ALBEDO, 1.3 DENSITY]**

NEAR SHOEMAKER "PONDED" DEPOSITS
NATURE AND DISTRIBUTION



- APPEAR TO BE RESULT OF DOWN SLOPE MOVEMENT
  - WHAT ARE THE RESOURCE IMPLICATIONS?
    - SIZE DISTRIBUTION?
    - DENSITY?
    - ELECTROSTATIC PROPERTIES?

NASA/APL: ROBINSON, ET AL, 2001, NATURE, V, 413.



METAL DOMINATED REGOLITH

KLEOPATRA ARECIBO RADAR IMAGESAND RECONSTRUTIONS
(OSTRO, ET AL, 2000, SCIENCE, 288

- **IRONS (M-TYPE) AND STONY IRONS (S-TYPE)**
  - **PLATINUM GROUP METALS**
  - **MANUFACTURING METALS**
  - **SOLAR WIND VOLATILES (?)**
- **EXAMPLE:**
  - **KLEOPATRA [MAIN BELT M-TYPE ASTEROID]** (Ostro, et al, 2000, Science, 288)
    - **RADAR: 217X94X81 KM, DUMBELL SHAPE, 3.5 GM/CM3 REGOLITH**
    - **POWDERED METAL REGOLITH**
  - **1986 DA [NEAR-EARTH M-TYPE ASTEROID]**

SILICATE / METAL MIXED REGOLIGH

- STONY IRONS (S-TYPE)
- PROBABLY WOULD COMPLICATE CONCENTRATION PROCESSES
- OTHERWISE, MAY BE BEST FOR SPACE MANUFACTURING
  - DIVERSITY OF PRODUCTS
- EXAMPLE:
  - CASTALIA [EARTH-CROSSING ASTEROID]
    - 2.1 REGOLITH DENSITY

DORMANT COMETS

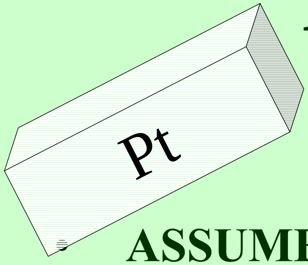
- HYDROCARBON / DUST CRUST (?)

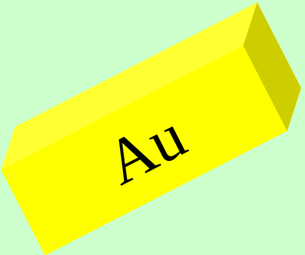
- ICE-RICH BENEATH CRUST
  - WATER, HYDROGEN, OXYGEN

ASTEROID RESOURCE ISSUES

- ACCESS TO CAPITAL MARKETS
  - COST OF CAPITAL
    - HIGH RISK = HIGH COST
    - REQUIRES HIGH RETURNS ON INVESTMENT
  - BRIDGE FUNDS TO COVER 10-15 YEAR START-UP WITHOUT A RETURN ON INVESTMENT
    - GOVERNMENT PARTICIPATION (?)
    - EARLY SPINOFF TECHNOLOGY NOT OBVIOUS
- LOW COST LAUNCH ACCESS
  - DEVELOPMENT MIGHT BE SHARED WITH LUNAR ENTERPRISE OR MARS PROGRAM
- RECURRING OPERATIONAL COSTS UNDEFINED
- COST OF 100%RELIABILITY IF AUTOMATED
  - COST OF HUMANS IF NOT AUTOMATED
- OPERATIONAL PROBLEMS
  - VERY LOW GRAVITY
  - ROTATION
- VARIABLE LOCATION OF ASTEROID RELATIVE TO EARTH
- COMPETITION FROM SOME COMPARABLE LUNAR RESOURCES
- SIZE OF IN-SPACE MARKET UNCERTAIN
- ECONOMIC IMPACT ON TERRESTRIAL MARKETS FOR PRECIOUS METALS

ASTEROID RESOURCE VALUES





- **ASSUME 100 PPM PRECIOUS METAL CONCENTRATION**
  - **SAME AS SOME METEORITES**

- **CURRENT TERRESTRIAL PRODUCTION ~3000 TONNES PER YEAR**
  - **WORTH ~$30-40 BILLION PER YEAR**
    - **NEW SUPPLY THAT COULD UNDERSELL WOULD DEFLATE VALUE**
    - **SIGNIFICANT WORLD WIDE PRIVATE AND GOVERNMENTAL OPPOSITION TO SUCH COMPETITION FROM SPACE**
      - **JOBS**
      - **NATIONAL REVENUE (AUSTRALIA, CANADA, SOUTH AFRICA, RUSSIA, CHILE, ETC.)**
- **LATER WE WILL COMPARE TO INTRODUCTION OF FUSION POWER BASED ON LUNAR HELIUM-3**
  - **GRADUAL AND LESS THREATENING ECONOMICALLY IN SHORT TERM**
  - **FIRST 100KG HELIUM-3 SHIPMENT TODAY WORTH ~$71 MILLION RELATIVE TO COAL**

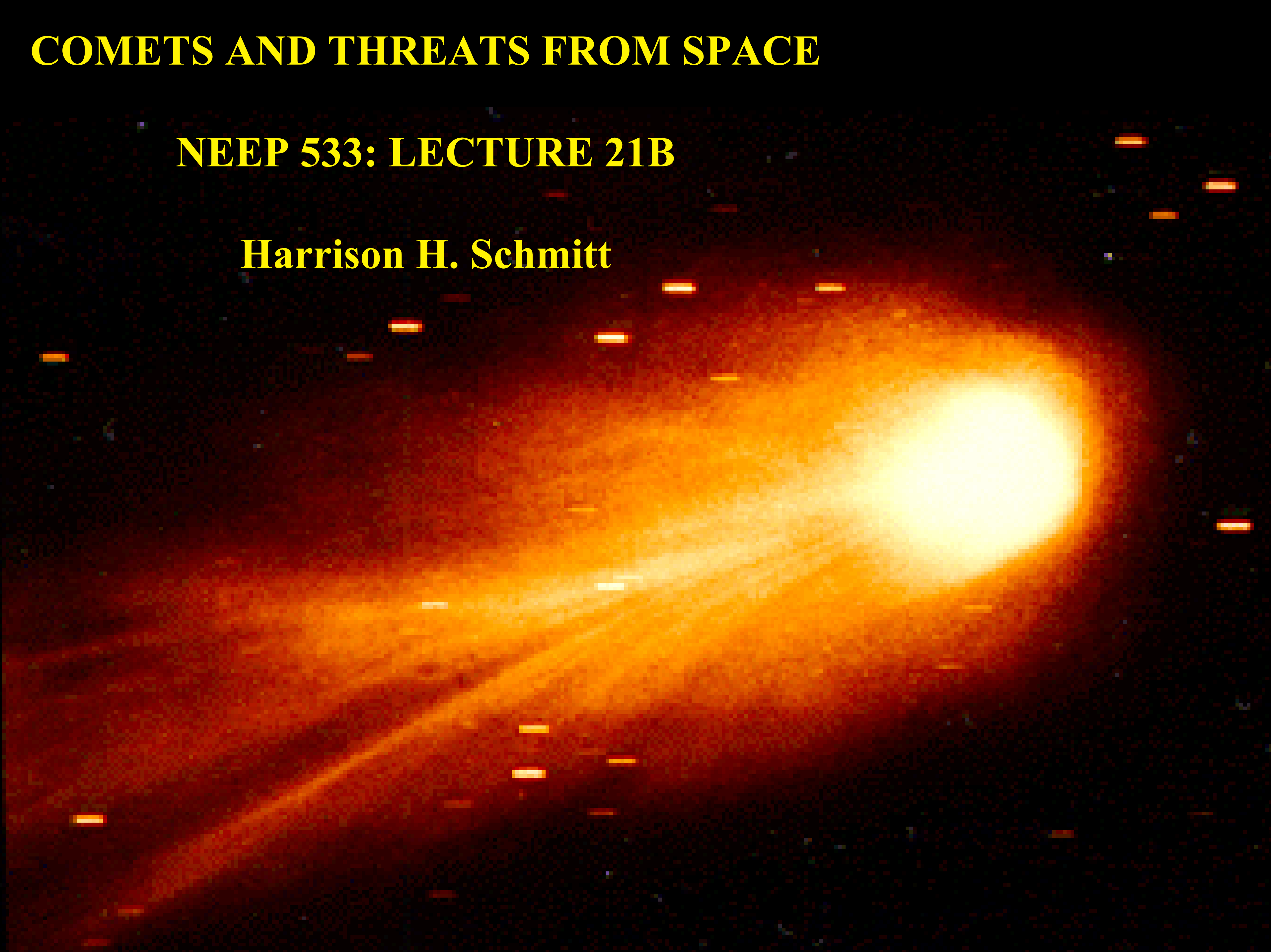
ASTEROID RESOURCES SELECTED REFERENCES

- **LEWIS, ET AL, 1993, <u>RESOURCES OF NEAR EARTH SPACE</u>, UNIV. ARIZONA PRESS.**
- **SPACE RESOURCE ROUNDTABLE PUBLICATIONS, M. DUKE, CO. SCHOOL OF MINES.**
- **INGEBRETSEN, 2001, (REVIEW) IEEE SPECTRUM, AUGUST.**
- **NEAL, V., ET AL., 1989, (CONSIDERATIONS FOR EVA ON PHOBOS), NASA-17779, SECTION 6.0** http://silver.neep.wisc.edu/~neep602/LEC16/neal.html**.**
- **KARGEL, J.S., 1996, (MARKET VALUES) SPACE 96**

COMETS AND THREATS FROM SPACE

NEEP 533: LECTURE 21B

Harrison H. Schmitt

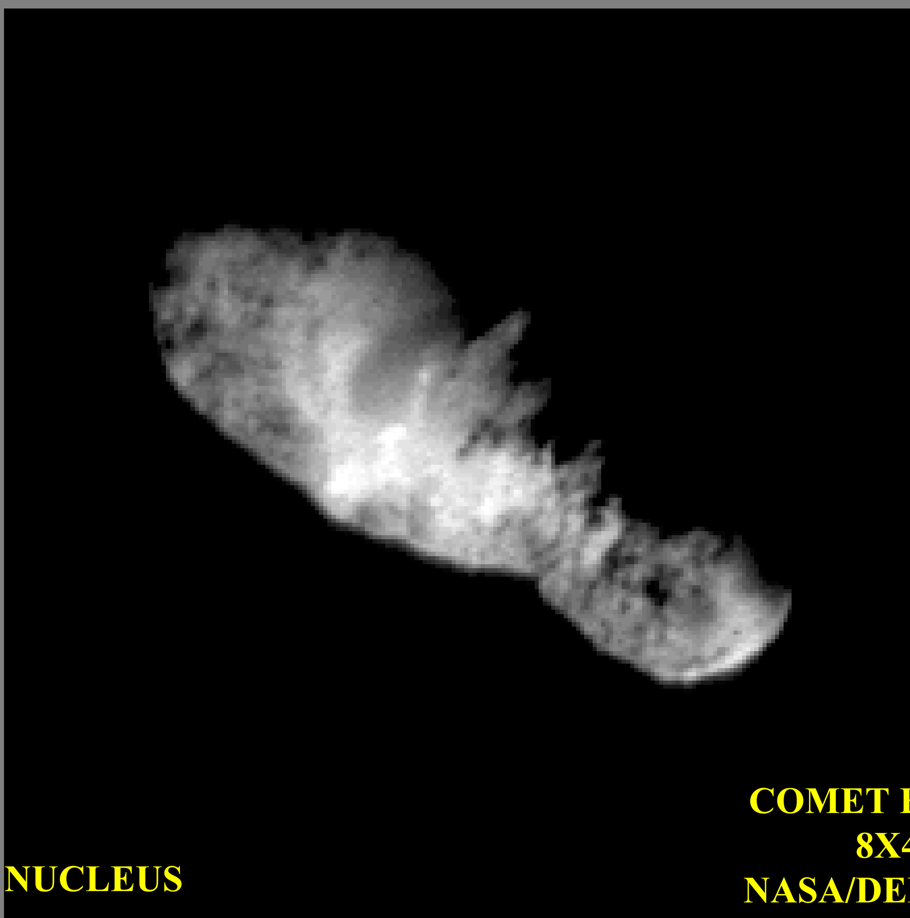


COMETS

SHORT PERIOD: FROM KUIPER BELT
LONG PERIOD: FROM ÖORT CLOUD

MANY IMPACT JUPITER AND THE SUN

MAY BE A TRANSITION IN ORBITAL CHARACTERISTICS AND COMPOSITION BETWEEN A FEW ASTEROIDS AND COMETS



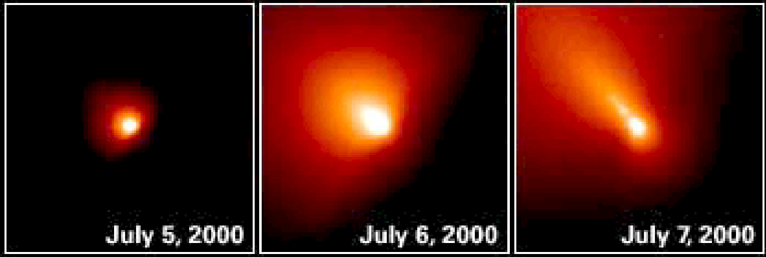
COMET BOR
8X4 KM
NASA/DEEP S

COMETS

Comet Hyakutake -HST

CHURYUMOV-GERASIMENKO
PUCKETT PHOTO

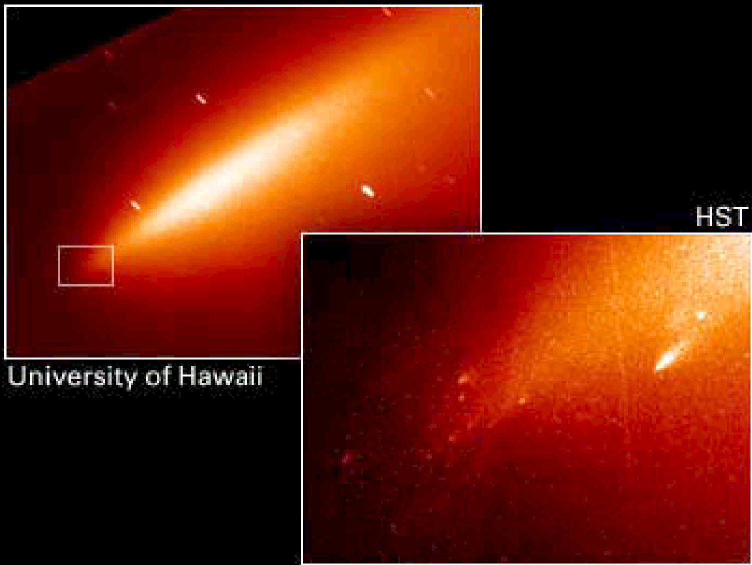
SCHWASSMAN-WACHMANN- 3
PUCKETT PHOTO

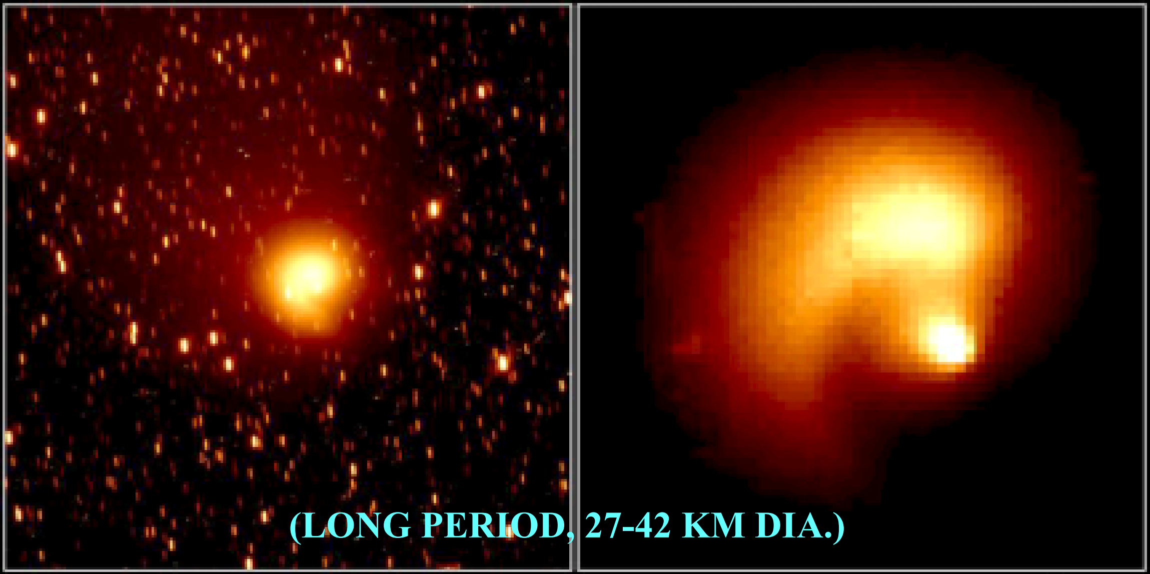


COMET LINEAR BREAKUP - HST

NH_3 DATA INDICATES FORMATION BETWEEN SATURN AND URANUS (KAWAKITA,2001, 294, SCIENCE)

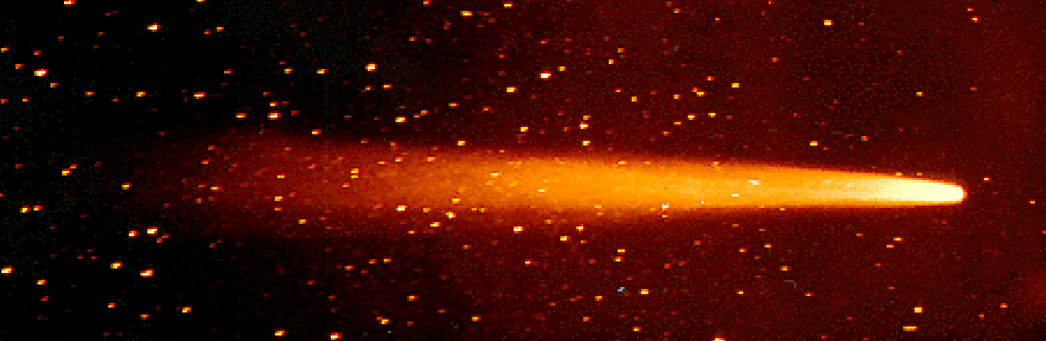
COMET LINEAR MISSING PIECES - HST





(LONG PERIOD, 27-42 KM DIA.)

Comet Hale-Bopp HST · WFPC2
PRC95-41 · ST ScI OPO · October 5, 1995 · H. Weaver (ARC), P. Feldman (JHU), NASA

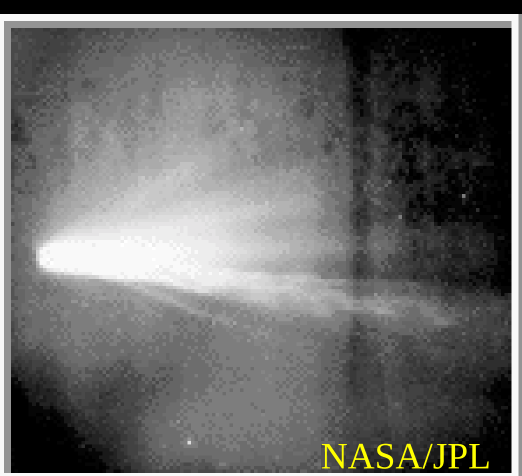


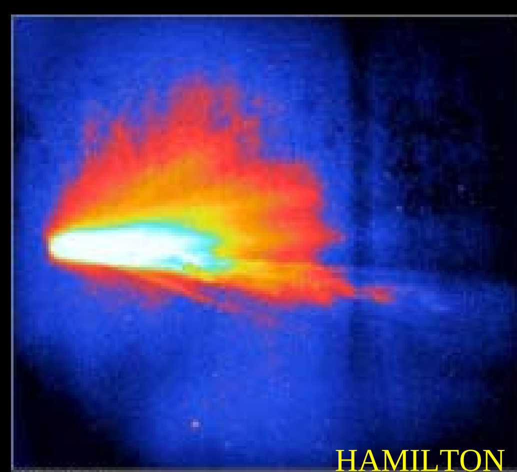
COMET HALLEY

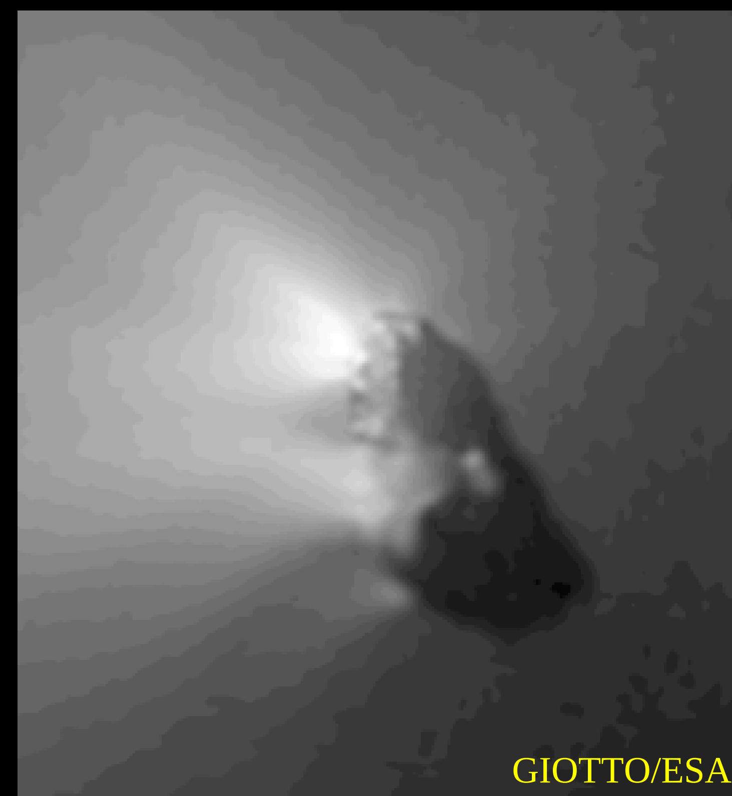
16X8X8 KM

~ 1 GM/CM^3

76 YR PERIOD







COMPOSITION OF COMET HALLEY

ICES (50%)

- **WATER (80%)**
- **CO (15%)**
- **ORGANICS**
  - **FORMALDEHYDE, CO_2, METHANE AND HYDROCYANIC ACID**

<u>D/H RATIO</u> ~3.2×10^{-4}

VS 1.56×10^{-4} FOR TERRESTRIAL OCEAN WATER AND AN ESTIMATED SOLAR NEBULA VALUE OF $<1 \times 10^{-4}$ (Meier, 1998)

DUST (50%)

ROCK (?)

COMET HALE-BOPP

LONG PERIOD

30-40 KM DIAMETER

THREE TAILS (EOS, 1998,79, 573-574):

BRIGHT WHITE DUST TAIL FORMED BY SOLAR RADIATION PRESSURE ON DUST

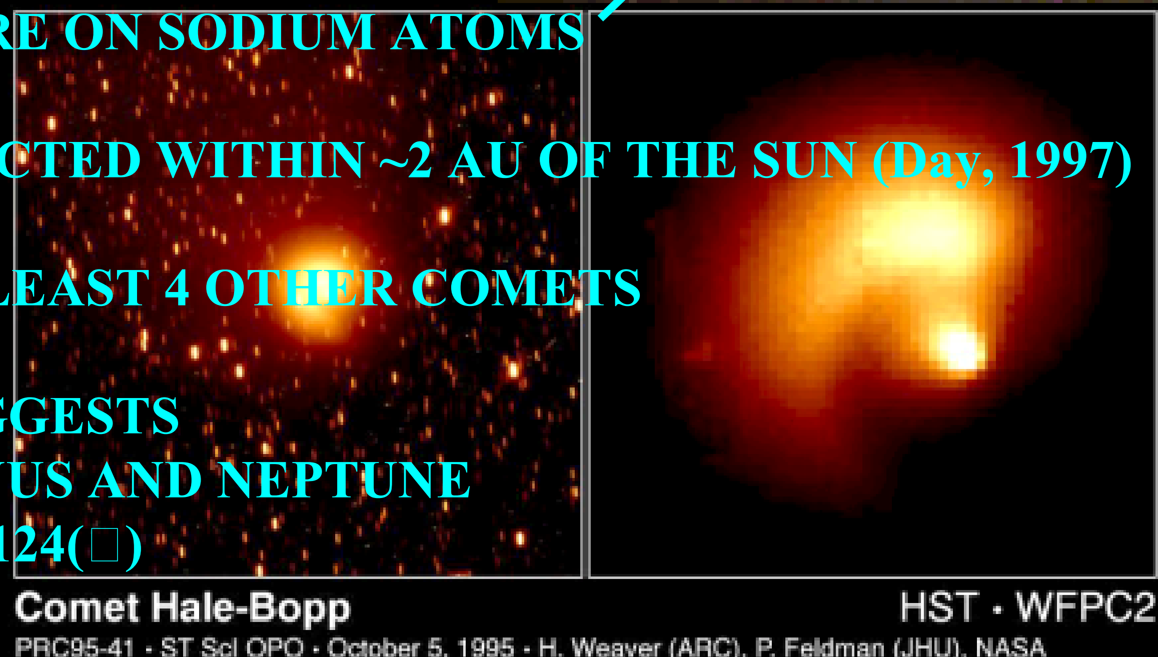
DIM BLUE ION TAIL FORMED BY SOLAR WIND AND COMETARY ION INTERACTION

SODIUM TAIL FORMED BY SOLAR RADIATION PRESSURE ON SODIUM ATOMS

X-RAY EMISSIONS DETECTED WITHIN ~2 AU OF THE SUN (Day, 1997)

CONFIRMED ON AT LEAST 4 OTHER COMETS

ARGON DETECTION SUGGESTS ORIGIN BETWEEN URANUS AND NEPTUNE (Science, 288, p. 2123-2124(□))



COMPOSITION COMET HALE-BOPP

CO_2, H_20, CO, CH_3OH (Jewit, et al., 1996)

<u>D/H RATIO</u> ~$3.3 \pm 0.8 \times 10^{-4}$,VS 1.56×10^{-4} FOR TERRESTRIAL OCEAN WATER AND AN ESTIMATED SOLAR NEBULA VALUE OF $<1 \times 10^{-4}$ (Meier, 1998)

CN COMPOUNDS

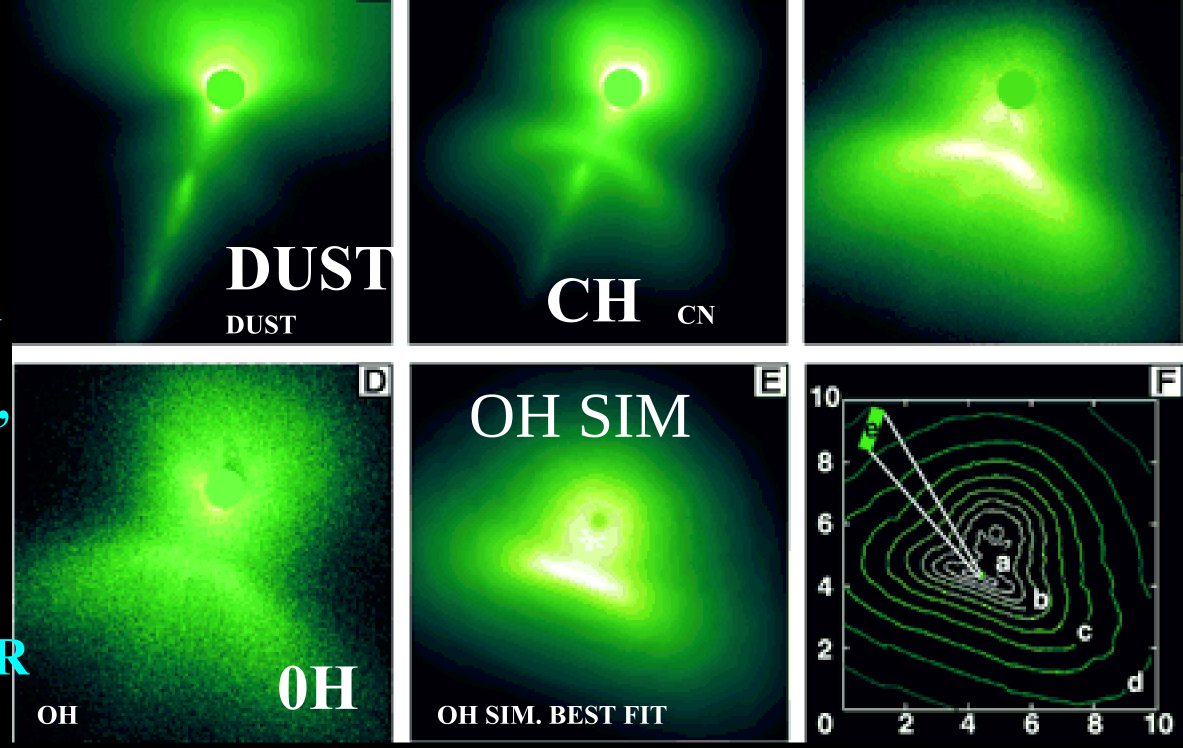
C, N, AND S, ISOTOPIC RATIOS SHOW ORIGIN IN THE SOLAR SYSTEM AND NOT INTERSTELLAR (Jewitt, et al., 1997)

COMET HYAKUTAKE

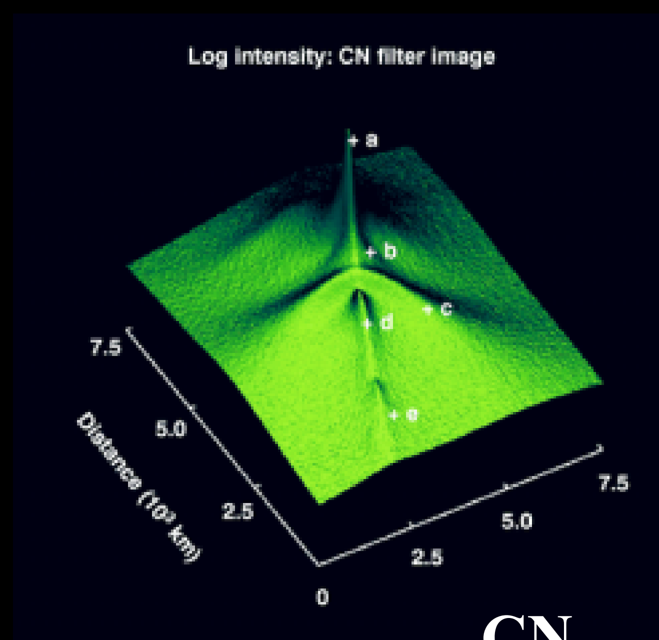
2 KM DIAMETER/6.5 HR ROTATION

UNUSUAL X-RAY AND E-UV EMISSIONS (Lisse, et al., 1996, Bingham, etal, 1997, Haberli, et al., 1997)

INTERACTION WITH SOLAR WIND AND SOLAR MAGNETIC FIELD



(HARRIS, ET AL, 1997, SCIENCE, 277)



ION TAIL DETECTED 3.8AU FROM NUCLEUS

(JONES, ET AL, 2000, NATURE, 404)

COMPOSITION
COMET HYAKUTAKE

ABUNDANT ETHANE (C_2H_6) AND METHANE (CH_4) (Mumma, et al., 1996)

CN

AMMONIA, ACETYLENE,METHANOL, METHYLCYANIDE, FORMALDEHYDE, AND HYDROGEN SULFIDE

H_20 (6 TONS / SEC)

DIATOMIC SULFUR

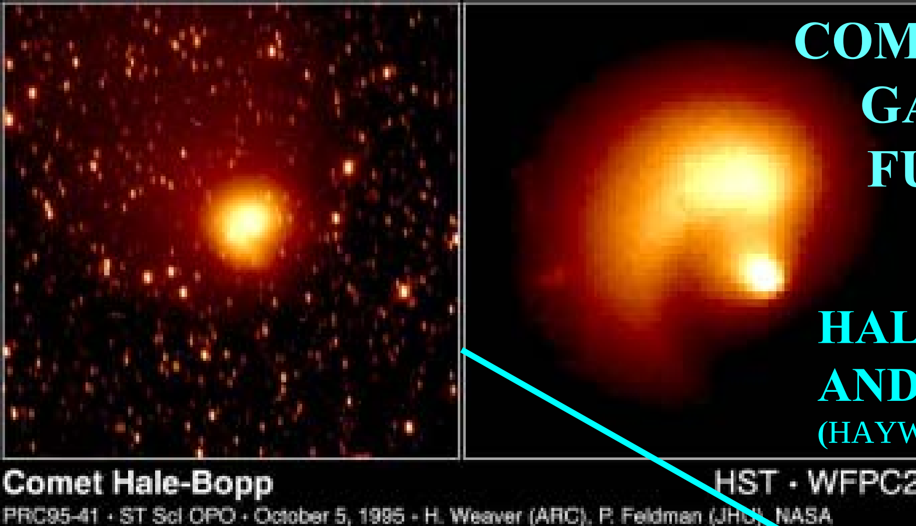
LITTLE CO

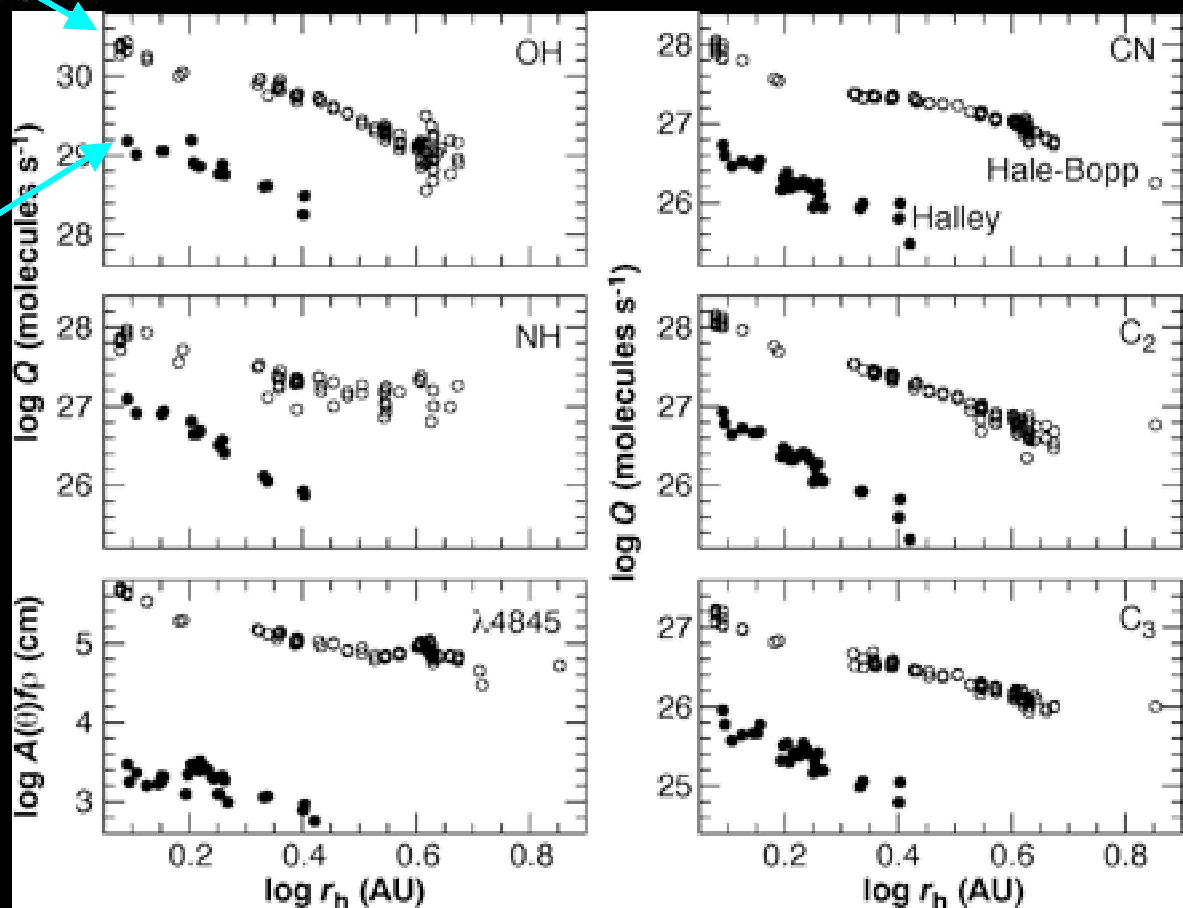
COMET HALE BOPP AND COMET HALLEY GAS SPECIES PRODUTION RATES AS FUNCTION OF DISTANCE FROM SUN

(SCHLIECHER, ET AL, 1997. SCIENCE, 275)

HALE-BOPP DUST COMPOSED OF OLIVINE AND AMORPHOUS SILICATE MATERIAL

(HAYWARD AND HANNER, 1997, SCIENCE, 275)





KUIPER BELT -1

(SEE BROWN, 2004, PHYSICS TODAY, APRIL)

INNER BELT

BEYOND NEPTUNE ORBIT BUT IN 3:2 ORBITAL PERIOD RESONANCE WITH NEPTUNE

>800 IDENTIFIED TO DATE

INCLINED, ELLIPTICAL, DYNAMICALLY STABLE ORBITS

CLASSICAL BELT AND SCATTERED DISK

OUTSIDE THE 3:2 RESONANCE WITH NEPTUNE

LOW INCLINATION, CIRCULAR, NON-RESONANT ORBITS

SCATTERED CLASS

INCLINED, ELLIPTICAL, VERY LARGE ORBITS

KUIPER BELT -2

DIAMETERS LARGELY 100-400 KM

WIDE RANGE OF COLORS, GENERALLY IN THE REDS OR GRAYS

TOTAL MASS 100S TIMES ASTEROID BELT

ESTIMATED >10^8 OBJECTS > 10 KM DIAMETER

(COCHRAN, ET AL, 1995, ASTRO. JOURNAL, 110)

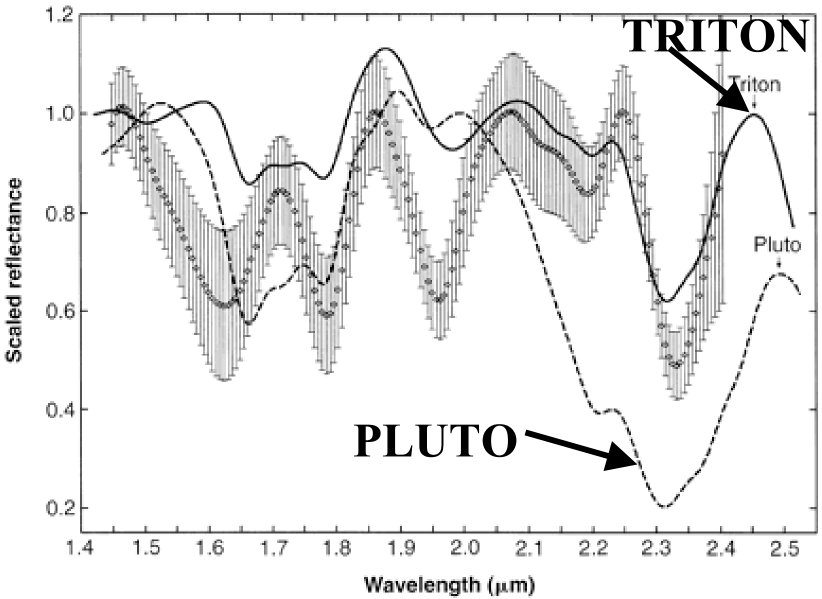
MAY HAVE INCLUDED PLUTO (2300 KM) AND ITS MOON CHARON (1100 KM, 6 HR ROTATION RATE)

ALSO THE CENTAUR AND TROJAN OBJECTS IN THE JUPITER /NEPTUNE REGION

>160 COMETS CONTROLLED BY JUPITER

(LEVINSON, 1996)

KUIPER BELT -3



OBJECT 1993SC SPECTRA SHOW PRESENCE OF SIMPLE HYDROCARBON ICE (CH_4, ETC) AS WELL AS MORE COMPLEX HYDROCARBONS.
(BROWN, ET AL, 1997, SCIENCE, 276)

SOME OBJECTS OUTSIDE THE ORBIT OF NEPTUNE

- **OBJECT 2000 CR_{105}**
- **~400KM IN DIAMETER**
- **PERIGEE 6.6B KM OUTSIDE NEPTUNE'S ORBIT**
- **PERIOD 3175 YEARS**

COMET HALE-BOPP
~ 40KM DIAMETER

KUIPER BELT -4

PRIMORDIAL MASS ESTIMATE IS 30 EARTH MASSES

CURRENT MASS ESTIMATE IS 0.06-0.3 EARTH MASSES

EARLY INTERACTIONS WITH NEPTUNE MAY EXPLAIN THE DIFFERENCE

COULD THIS BE A SOURCE FOR THE IMPACTORS DURING THE LARGE BASIN STAGES OF LUNAR EVOLUTION AT 4.1-3.9 BY? (see Malhotra, 1993)

CONSIDER THAT NEPTUNE MAY HAVE FIRST FORMED IN AT ~20 AU AND CLOSER TO SATURN

NET INCREASE IN ANGULAR MOMENTUM THROUGH INTERACTIONS WITH KUIPER PRECURSORS, DRIVING THEM BOTH OUTWARD AND INWARD

KUIPER BELT - 5

OBJECT 1993C IN KUIPER BELT BELT (Brown, 1997)

IR SPECTRA SUGGEST HYDROCARBON ICE (METHANE, ETHANE, ETHELENE OR ACETYLENE AND POSSIBLY MORE COMPLEX COMPOUNDS)

OBJECT 1996 TO66 IN KUIPER BELT (Science News, 1998, 154, 310; Luu and Jewitt, 1998))

- **BRIGHTER THAN OTHER KNOWN OBJECTS**
- **IR ABSORPTION ABSENT**
- **~600 KM DIAMETER**
- **6.25 HR ROTATION**

QUAOAR AT 23 AU IS 1250 KM IN DIAMETER

Quaoar Compared by Diameter with Other Solar System Bodies

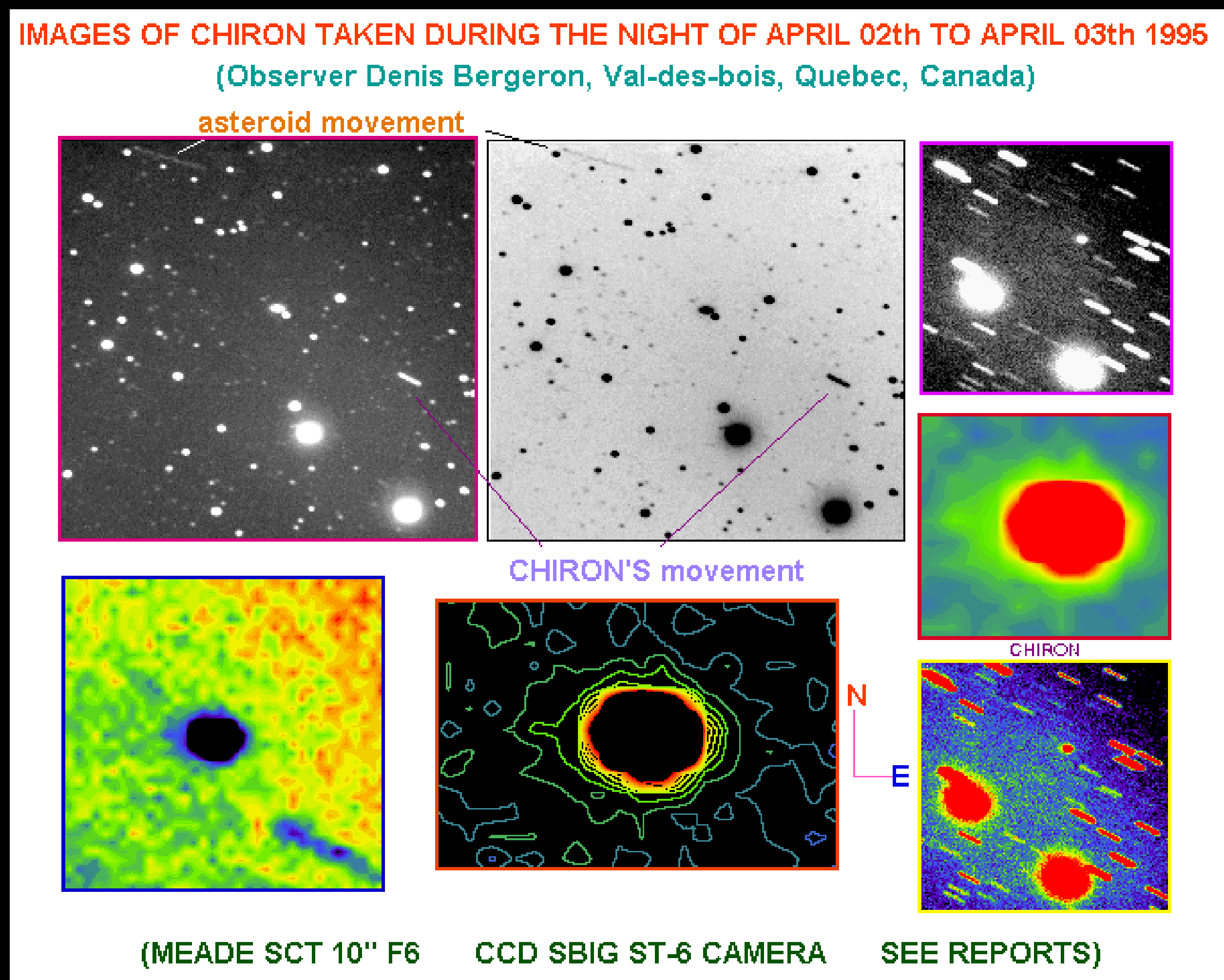
CHIRON - "ESCAPED KUIPER BELT OBJECT (?)

PERI. 8.46 AND APHE. ~19 AU
BETWEEN JUPITER & URANUS
ORBIT INCLINATION 6.93°

148-208 DIAMETER

ROTATION 5.9 HRS

PRESENCE OF COMA AT LOW T
>2 M KM DIAMETER
INDICATES CH_4, CO_2, OR N_2
DUST ATMOSPHERE
~1200 KM DIAMETER



ÖORT CLOUD

- SOURCE OF COMETS WITH LONG PERIODS
  - PROPOSED BY JAN ÖORT

- NO DIRECT OBSERVATIONAL EVIDENCE
  - BUT 1600 KM DIA. SEDNA MAY BE RELATED TO THE ÖORT CLOUD
    - 900 X 76 AU ORBIT
- MAY EXTEND FROM 20,000 TO 100,000 AU

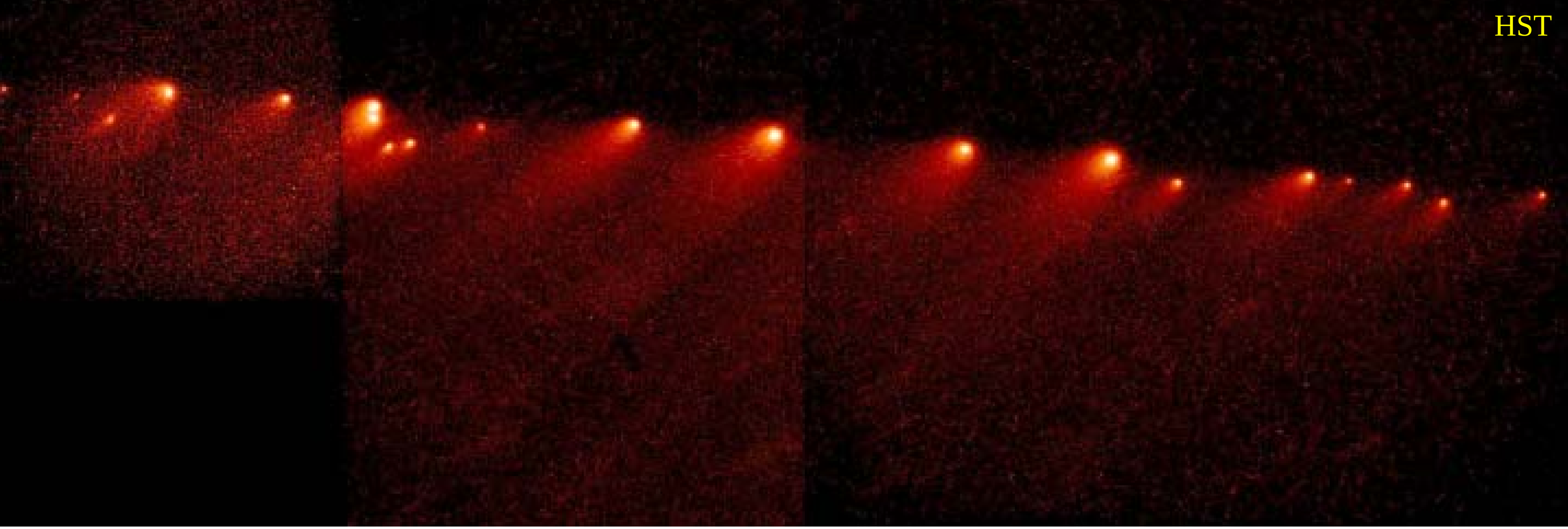
- FRAGMENTS FROM THE OUTER PLANETS REGION
- PROPELLED OUTWARD BY INTERACTION WITH THE GAS GIANTS

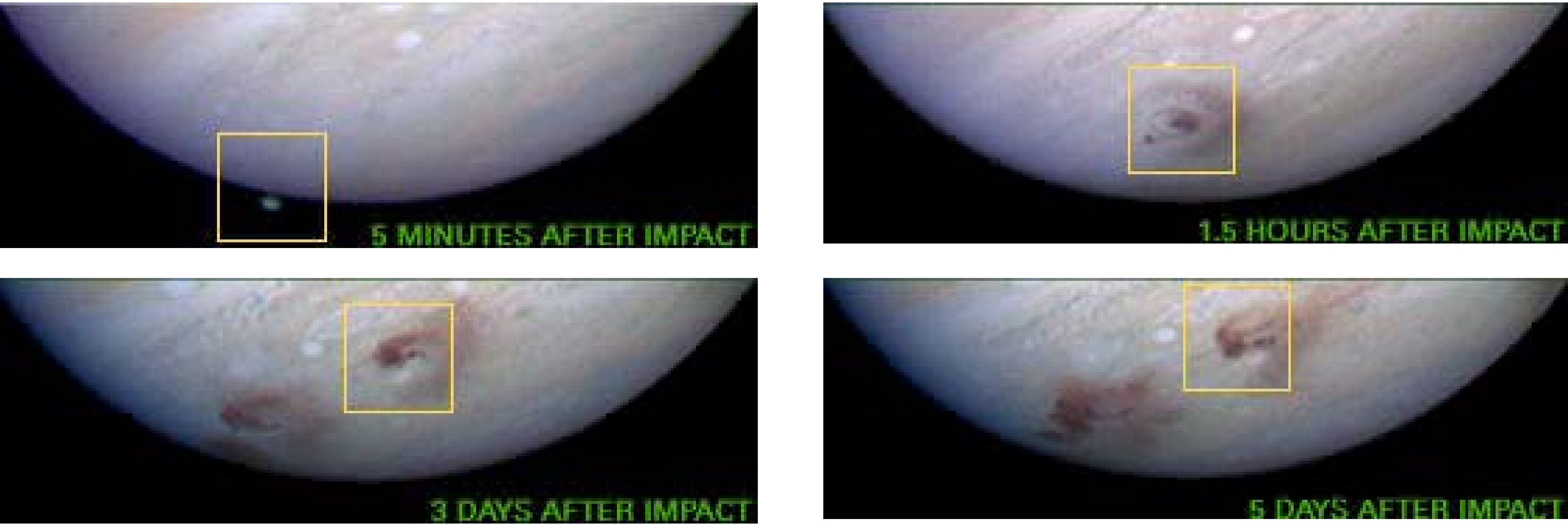
- THROWN BACK BY PASSING STARS
  - RANDOMLY PROGRADE AND RETROGRADE

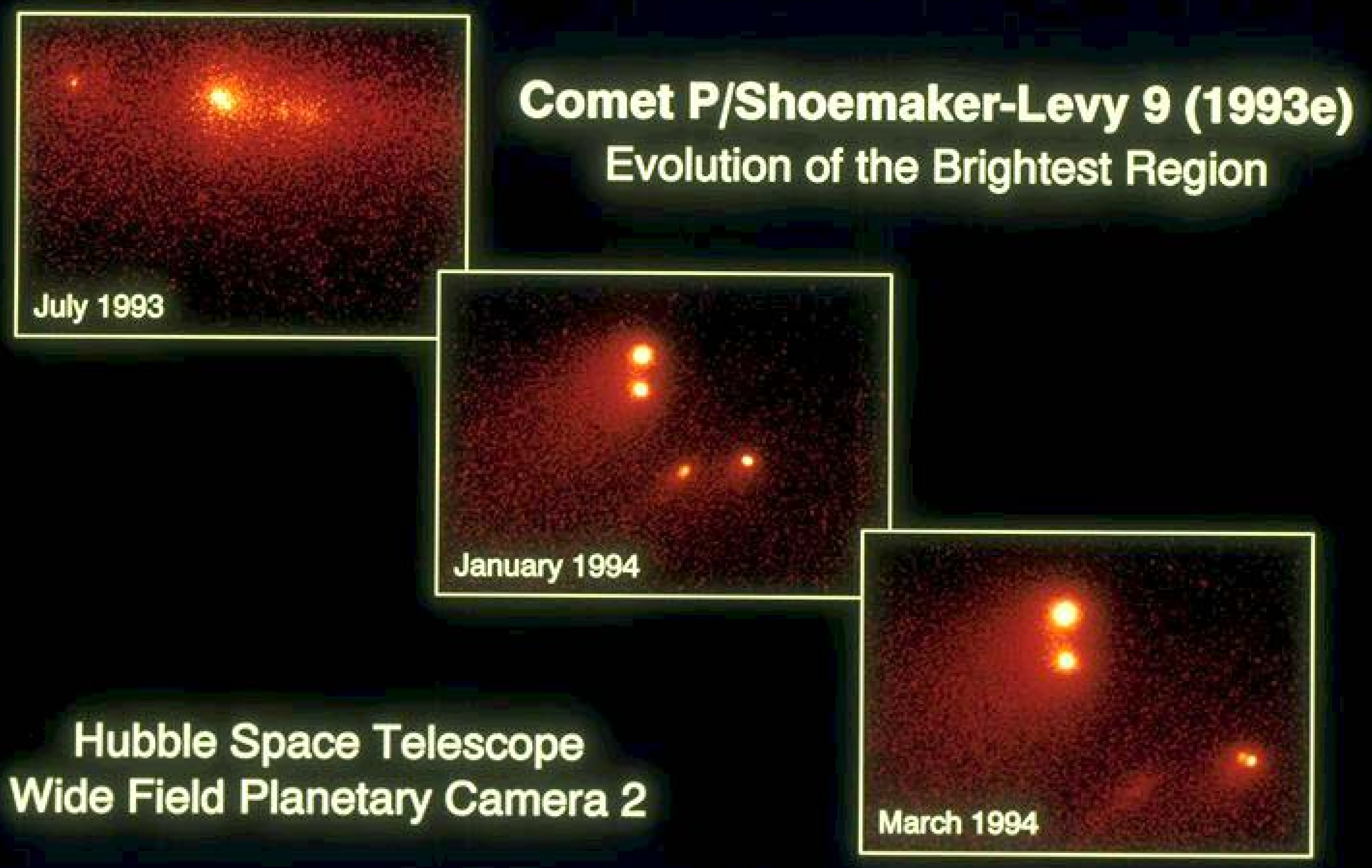
COMET HALLEY
76 YEAR PERIOD BUT ORIGINALLY MAY BE FROM INNER ÖORT CLOUD
(LEVISON, 2000, SCIENCE, 290)

COMET SHOEMAKER LEVY 9 ENCOUNTER WITH JUPITER

HST





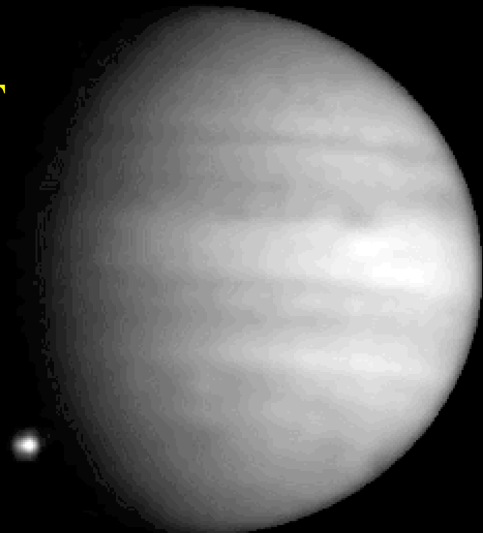

Comet P/Shoemaker-Levy 9 (1993e)
Evolution of the Brightest Region
July 1993
January 1994
March 1994
Hubble Space Telescope
Wide Field Planetary Camera 2

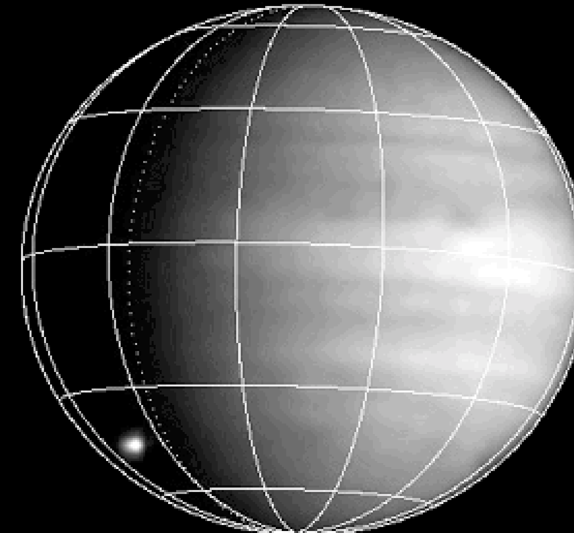
SHOEMAKER LEVY FRAGMENT W IMPACT ON JUPITER

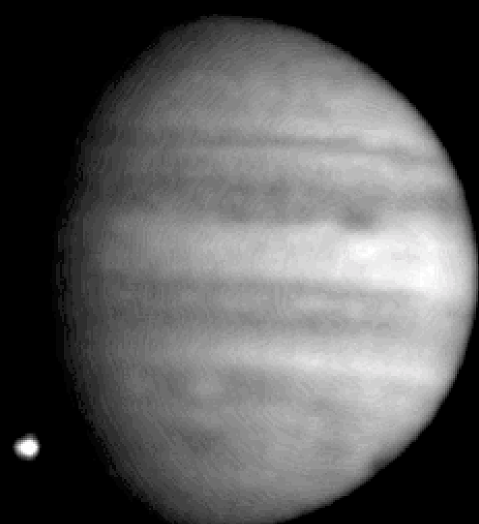
NASA/GALILEO/JPL

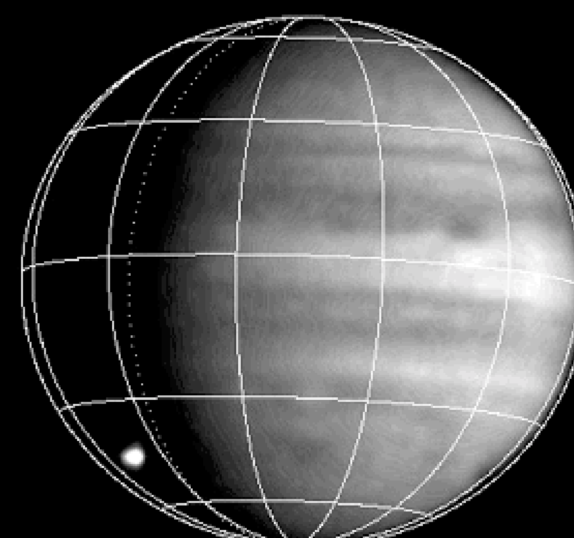
HUBBLE

KECK



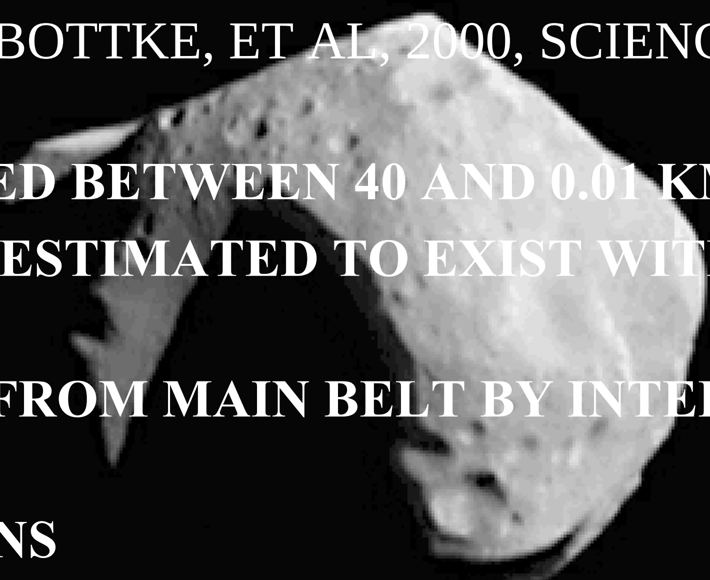






NEAR EARTH ASTEROIDS

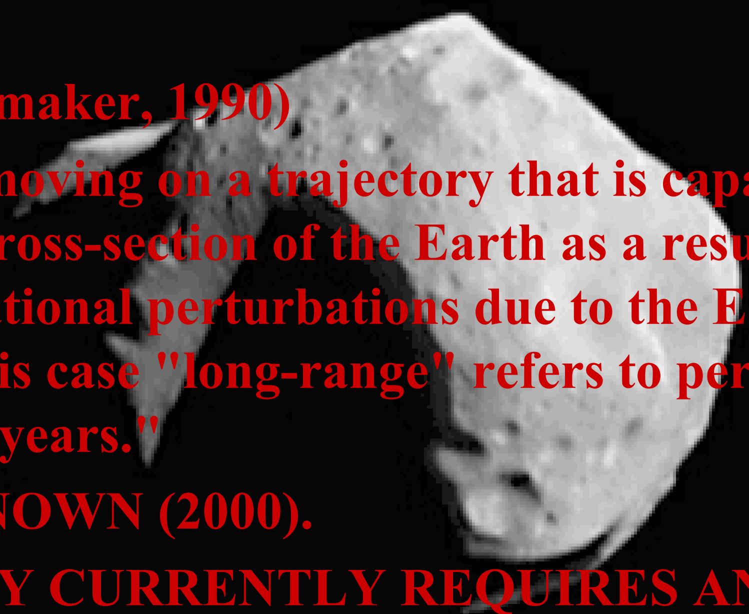
- **ESTIMATES ARE THAT ABOUT 2000 NEAS EXIST > 1 KM DIAMETER** (SEE BOTTKE, ET AL, 2000, SCIENCE, 288) **AND 1 MILLION > 50 M**
  - **~950 DETECTED BETWEEN 40 AND 0.01 KM DIAMETER**
  - **~900 OTHERS ESTIMATED TO EXIST WITH ~1 KM DIAMETER (H < 18)**
    - **EJECTED FROM MAIN BELT BY INTERACTIONS WITH JUPITER.**
    - **COLLISIONS**
      - **CHAOTIC DYNAMICS INCREASE ORBITAL ECCENTRICITY.**
    - **RELATIVELY SHORT (10-100 MYR) LIFETIMES AND THUS MUST BE REPLENISHED RAPIDLY COMPARED TO THE AGE OF THE SOLAR SYSTEM.**



MATHILDE 59X47 KM
ALBEDO 3-4%
17.4DAY ROTATION
DENSITY 1.3
C TYPE
NASA/NEAR/APL

EARTH-CROSSING ASTEROIDS (ECA)

- **CLASS OF NEAS WITH THE POTENTIAL TO IMPACT OUR PLANET**
- **DEFINITION (Shoemaker, 1990)**
  - **"..an object moving on a trajectory that is capable of intersecting the capture cross-section of the Earth as a result of on-going long-range gravitational perturbations due to the Earth and other planets. In this case "long-range" refers to periods of tens of thousands of years."**
- **170~ ECAS ARE KNOWN (2000).**
- **THEIR DISCOVERY CURRENTLY REQUIRES AN ABSOLUTE MAGNITUDE >13.5**
- **GENERAL NATURE**
  - **MAJORITY ARE DARK, C-TYPE ASTEROIDS (CARBONACEOUS CHONDRITE METEORITES)**
  - **LOW DENSITY, VOLATILE-RICH, MUCH OPAQUE (CARBON-BEARING?) MATERIAL**

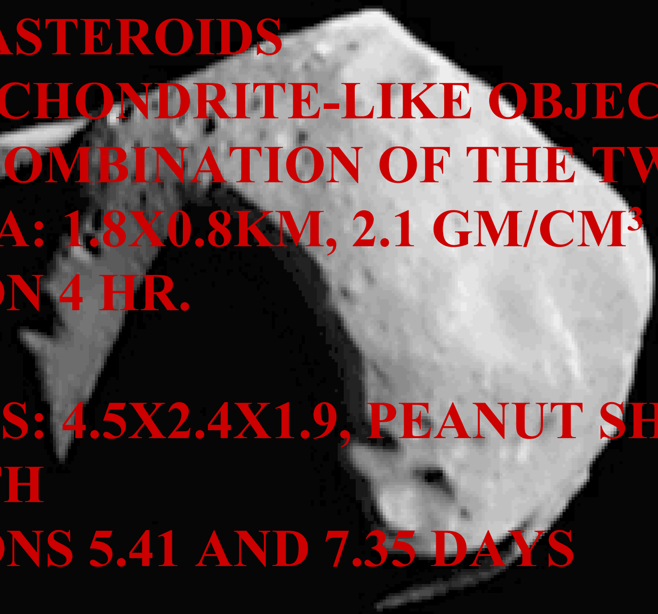


MATHILDE 59X47 KM
C-TYPE
ALBEDO 4% (6X<EROS)
1.3 GM/CM^3
NASA/NEAR/APL

EARTH-CROSSING ASTEROIDS (ECA) -2

GENERAL CHARACTERISTICS, CONTINUED

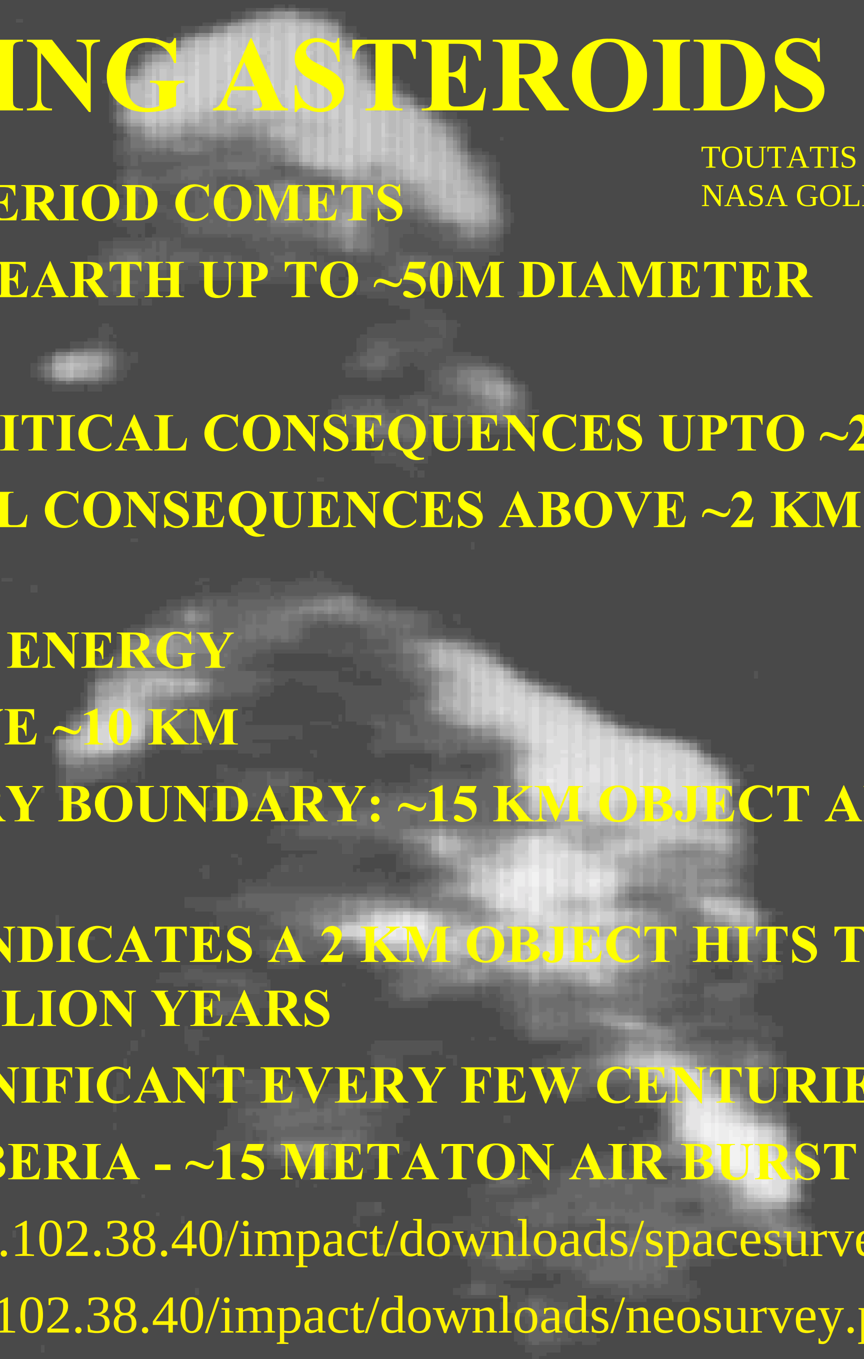
- MANY ARE S-TYPE ASTEROIDS
  - EITHER STONY, CHONDRITE-LIKE OBJECTS OR STONY-IRON OBJECTS OR A COMBINATION OF THE TWO.
    - CASTALIA: 1.8X0.8KM, 2.1 GM/CM^3 REGOLITH, ROTATION 4 HR.
    - TOUTATIS: 4.5X2.4X1.9, PEANUT SHAPE, 2.1 GM/CM^3 REGOLITH
      ROTATIONS 5.41 AND 7.35 DAYS



- A FEW METALLIC (NI-FE) AND BASALTIC TYPES.
- PHYSICAL CHARACTERISTICS
  - HIGHLY IRREGULAR SHAPES
  - WELL DEVELOPED REGOLITHS
  - SOME VERY RAPID SPINS
  - SOME MAY BE CONTACT BINARIES OR LOOSE AGGREGATES.

MATHILDE 59X47 KM
C-TYPE
ALBEDO 4% (6X<EROS)
1.3 GM/CM^3
NASA/NEAR/APL

EARTH CROSSING ASTEROIDS



TOUTATIS
NASA GOLDSTONE

- **ASTEROIDS AND SHORT PERIOD COMETS**
- **ATMOSPHERE PROTECTS EARTH UP TO ~50M DIAMETER**
  - **5 MEGATONS ENERGY**
- **GLOBAL ECONOMIC / POLITICAL CONSEQUENCES UPTO ~2 KM**
- **GLOBAL ENVIRONMENTAL CONSEQUENCES ABOVE ~2 KM DIAMETER**
  - **1 MILLION MEGATONS ENERGY**
- **MASS EXTINCTIONS ABOVE ~10 KM**
  - **CRETATOUS - TERTIARY BOUNDARY: ~15 KM OBJECT AND 100 MEGATONS**
- **STATISTICAL ANALYSIS INDICATES A 2 KM OBJECT HITS THE EARTH 1-2 TIMES PER MILLION YEARS**
  - **SMALLER EVENTS SIGNIFICANT EVERY FEW CENTURIES**
    - **1908 TONGUSKA, SIBERIA - ~15 METATON AIR BURST**
- 1992 SPACEGUARD http://128.102.38.40/impact/downloads/spacesurvey.pdf
- 1995 NEO SURVEY http://128.102.38.40/impact/downloads/neosurvey.pdf

NEAR EARTH OBJECTS (NEOs)
(INCLUDING ECAs)

- **ESTIMATED 2000 >1 KM DIAMETER**
  - **~50% DISCOVERED**
  - **1 IN 1000 CHANCE OF IMPACT ON EARTH EVERY 75 YEARS**
- **PROTECTION OPTIONS**
  - **DETECTION**
  - **INTERCEPT AND DIVERSION**
    - **HEAVY LIFT LAUNCH AND HIGH ISP, IN-SPACE PROPULSION SYSTEM (FISSION OR FUSION)**
    - **EXPLOSIVES PROBABLY NOT A GOOD IDEA**
      - **EXCEPT POSSIBLY FOR RUBBLE ONLY A FEW KM IN DIAMETER**

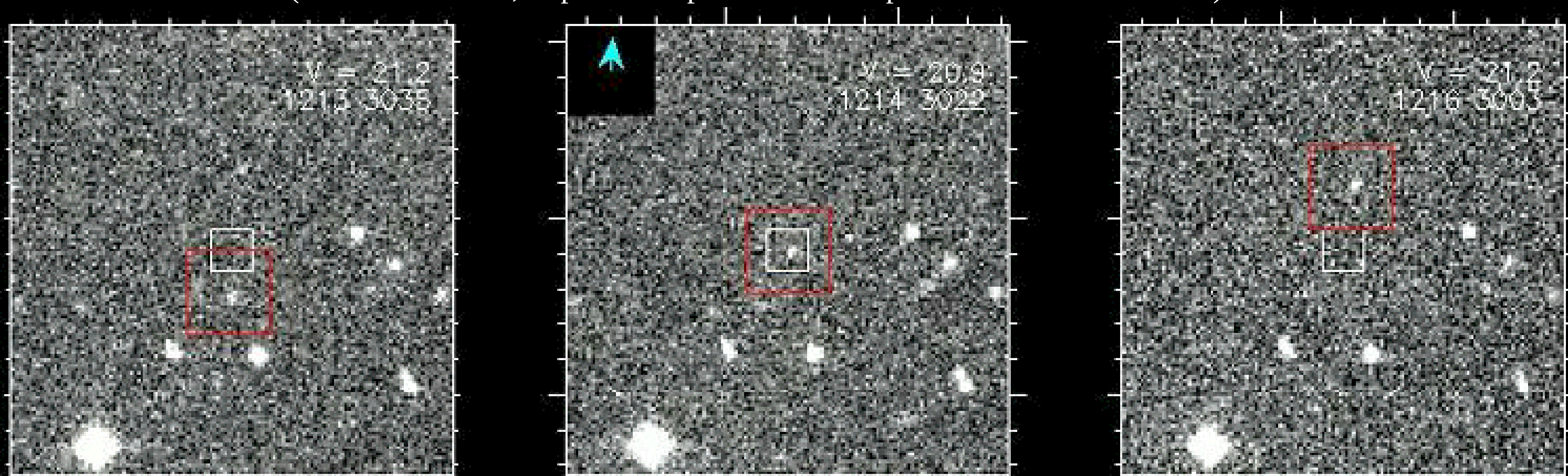
ECA 2000 BF 19

COLLISION COURSE WITH EARTHFOR IMPACT IN 2011!!!!

(http://impact.arc.nasa.gov/index.html)

FURTHER OBSERVATIONS INDICATED NO COLLISION WITHIN 50 YEARS.

(SPACEWATCH, http://www.lpl.arizona.edu/spacewatch/2000bf19.html)



SHOULD THE HUMAN SPECIES WORRY ABOUT THIS AND OTHER ASTEROID HAZARDS AND THE ASSOCIATED RISK?

SHOULD A DETECTION AND TRACKING SYSTEM BE A HIGH PRIORITY ALONG WITH EVERYTHING ELSE?

IF SO, SHOULD A CONTINUOUSLY UPGRADED CAPABILITY BE ESTABLISHED TO DEFLECT A THREATENING ECA?

THE TORINO SCALE

Assessing Asteroid and Comet Impact Hazard Predictions in the 21st Century

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.

NATURE OF THE ASTEROID HAZARD

"LOW PROBABLILITY - HIGH CONSEQUENCE" CATEGORY OF RISK
130+ KNOWN TERRESTRIAL CRATERS

<u>65M YEAR AGO EVENT GAVE MOST RECENT MASS EXTINCTION</u>
(ALVEREZ, ET AL, 1980; CYGAN, ET AL, 1996)

180 KM CRATER
~20,000 KM^3 OF MELT VOLUME
~10 KM OBJECT AT 15-20 KM/SEC
10-20% DECREASE IN INSOLATION
CO_2 / SO_2 EFFECTS DUE TO SULFATE-RICH ROCK AT IMPACT SITE
DEPRESSION OF GLOBAL TEMPERATURES
ACID RAIN?
OZONE DEPLETION?

<u>250M YEAR AGO EVENT GAVE 90%SPECIES EXTINCTION</u>

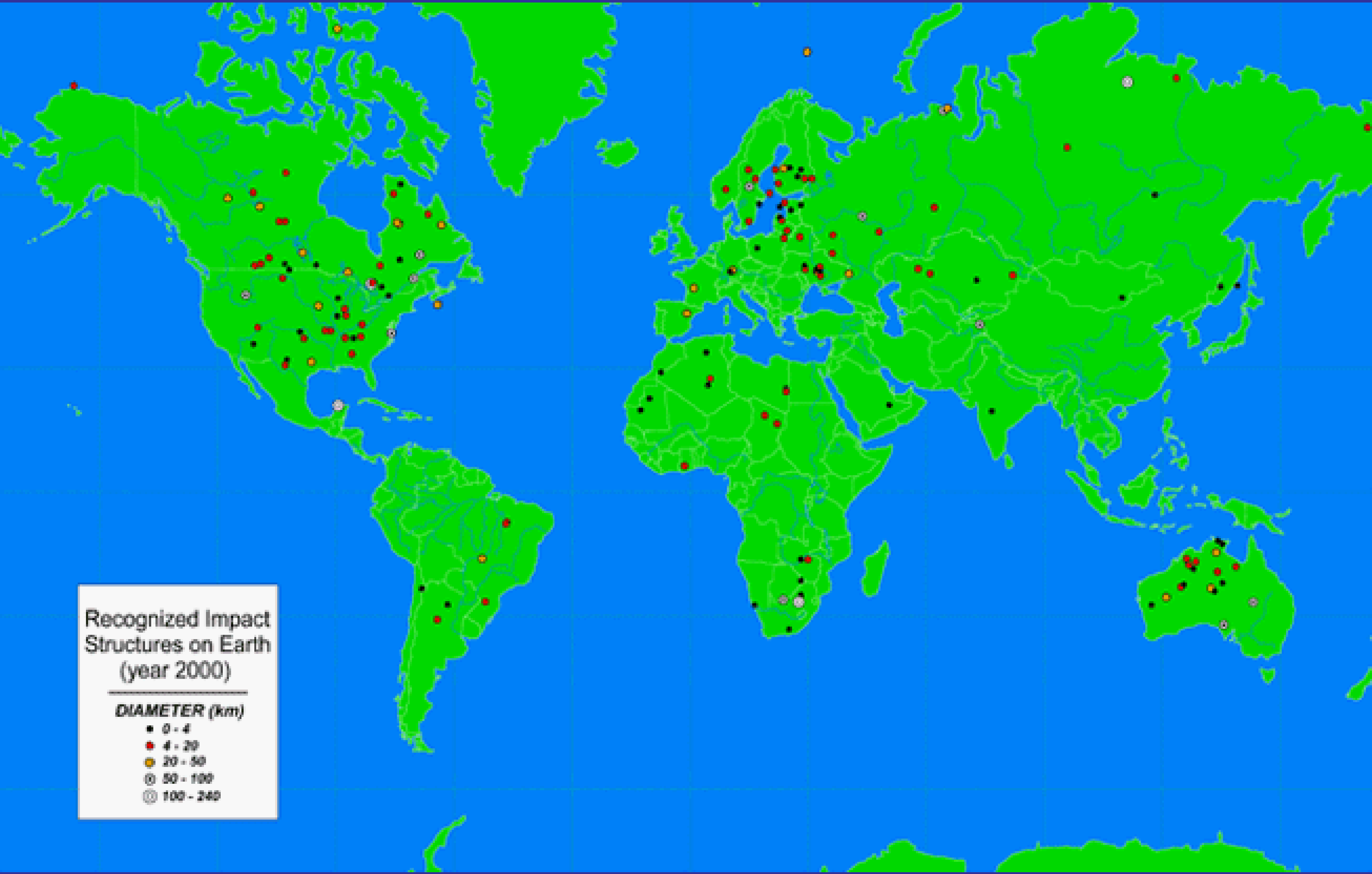
NATURE OF THE ASTEROID HAZARD

EFFECTS OF 1 KM OBJECT IMPACTING EARTH AT 20 KM/SEC

(SILVER AND SCHULTZ, 1982)

~26 KM CRATER WITH 100 TIMES MASS OF IMPACTOR EJECTED
CONTINOUS EJECTA TO 1+ CRATER DIAMETER
SECONDARY EJECTA TO MANY CRATER DIAMETERS
FIRE BALL AND EJECTA TO ABOVE THE ATMOSPHERE
TSUNAMI OF MASSIVE SCALE IF OCEAN IMPACT
LARGE QUANTITIES OF NO AT BOW SHOCK IN ATMOSPHERE
Cl_2 , CH_4 AND SO_2 FORMED IF OCEAN IMPACT
CO_2, SO_2, AND S_2 FROM CARBONATE AND SULFATE ROCKS
LARGE QUANTITIES OF FINE DUST (10% OF IMPACTOR?)
COMPLETE BLOCKAGE OF INSOLATION FOR 3-6 MONTHS ?

RIES EVENT 14M YEARS AGO GAVE 26 KM CRATER

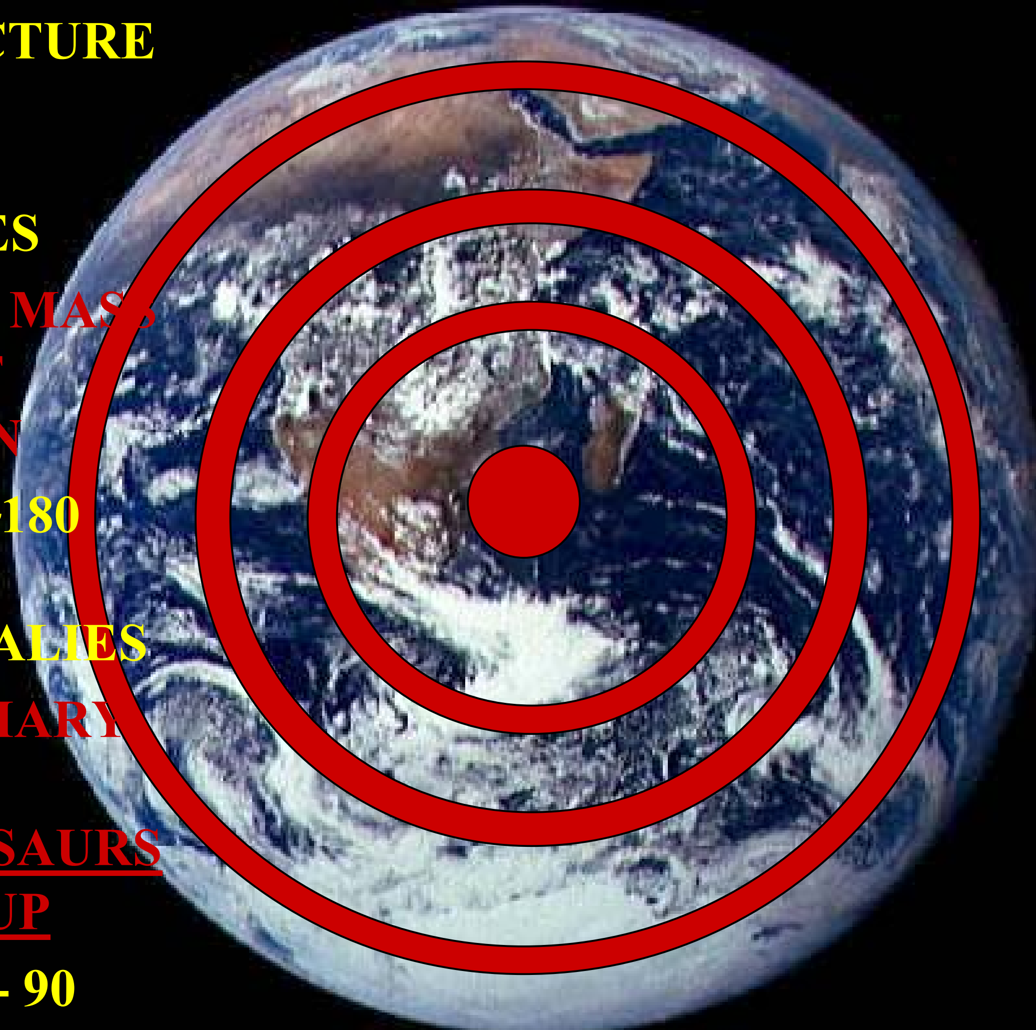

Recognized Impact Structures on Earth (year 2000)
DIAMETER (km)
0 - 4
4 - 20
20 - 50
50 - 100
100 - 240

MAJOR DOCUMENTED IMPACT RELATED EVENTS ON EARTH

- 4.5-3.8 B.Y. - PERIOD OF INTENSE CRATERING AND LARGE BASIN FORMATION (OLD ZIRCONS)
  - ASSISTANCE TO BUT ALSO PREVENTION OF PERMANENT LIFE DEVELOPMENT
- 2.6 B.Y. Ir ANOMALY, SILICATE SPHERULES
- 2.0 B.Y. VERTEFORT - 300 KM IMPACT STRUCTURE
- 1.85 B.Y. SUDBURY - >250 KM IMPACT STRUCTURE
- ~ 380 M.Y. - Ir & OTHER ANOMALIES , C ISOTOPE RATIOS, TSUNAMI BRECCIA,
  - INTRA-DEVONIAN (FRASNIAN/FAMENNIAN BOUNDARY) MASS EXTINCTION-

MAJOR IMPACT RELATED EVENTS ON EARTH

- 251 M.Y. - W. AUSTRALIA BURIED IMPACT STRUCTURE OR OCEAN IMPACT (?) - SULFUR RELEASE, ^{3}HE ANOMALY, FULLERENES
  - PERMIUM-TRIASSIC MASS EXTINCTION - MOST SEVERE YET KNOWN
- 65 M.Y. - CHICXULUB - ~180 KM BURIED IMPACT STRUCTURE / IR ANOMALIES
  - CRETACEOUS-TERTIARY BOUNDARY MASS EXTINCTION - DINOSAURS DOWN / MAMMALS UP
- 35.5 M.Y. CHESAPEAKE - 90 KM BURIED IMPACT STRUCTURE - TECTITES

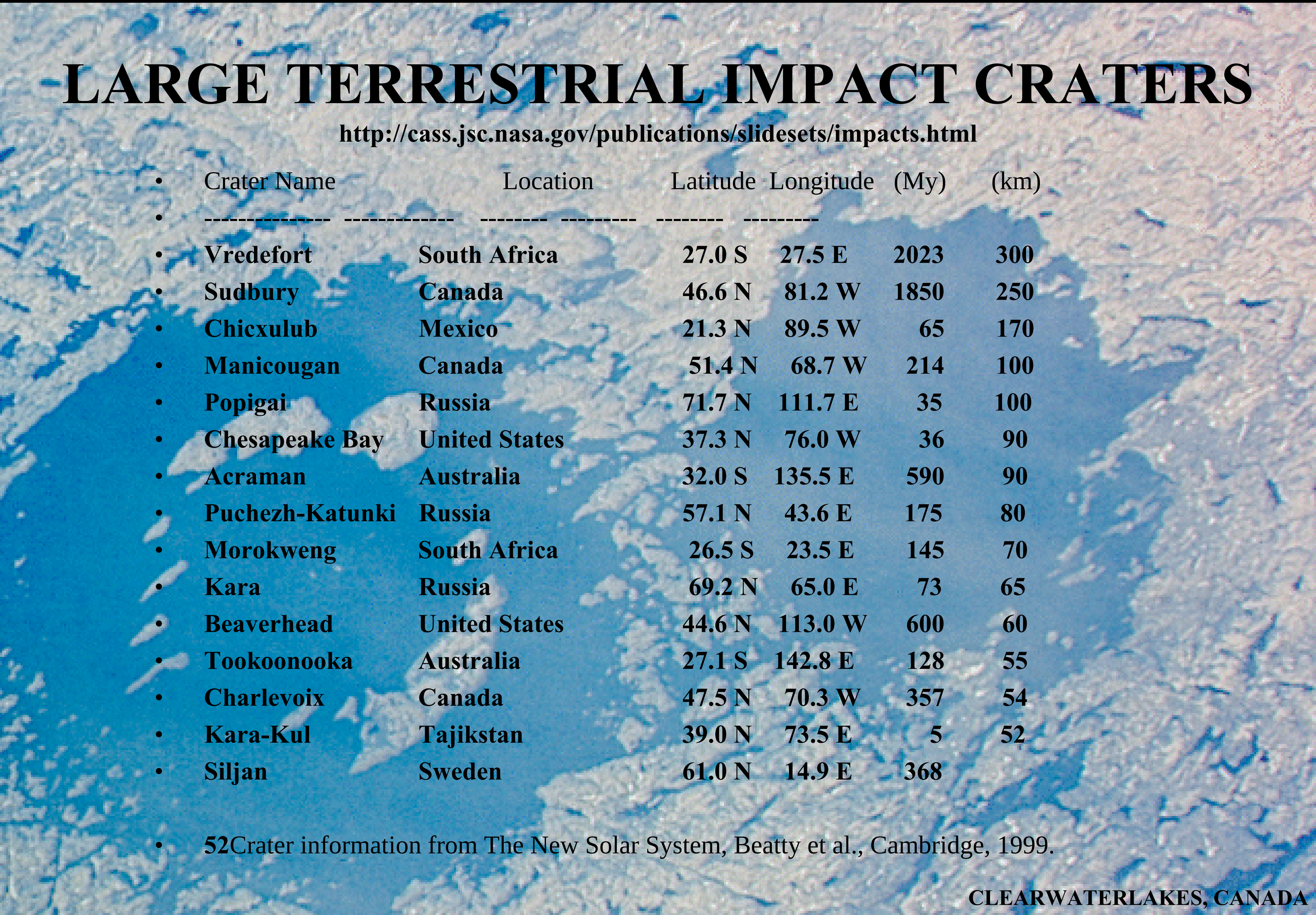


LARGE TERRESTRIAL IMPACT CRATERS

http://cass.jsc.nasa.gov/publications/slidesets/impacts.html

Crater Name	Location	Latitude	Longitude	(My)	(km)
Vredefort	**South Africa**	**27.0 S**	**27.5 E**	**2023**	**300**
Sudbury	**Canada**	**46.6 N**	**81.2 W**	**1850**	**250**
Chicxulub	**Mexico**	**21.3 N**	**89.5 W**	**65**	**170**
Manicougan	**Canada**	**51.4 N**	**68.7 W**	**214**	**100**
Popigai	**Russia**	**71.7 N**	**111.7 E**	**35**	**100**
Chesapeake Bay	**United States**	**37.3 N**	**76.0 W**	**36**	**90**
Acraman	**Australia**	**32.0 S**	**135.5 E**	**590**	**90**
Puchezh-Katunki	**Russia**	**57.1 N**	**43.6 E**	**175**	**80**
Morokweng	**South Africa**	**26.5 S**	**23.5 E**	**145**	**70**
Kara	**Russia**	**69.2 N**	**65.0 E**	**73**	**65**
Beaverhead	**United States**	**44.6 N**	**113.0 W**	**600**	**60**
Tookoonooka	**Australia**	**27.1 S**	**142.8 E**	**128**	**55**
Charlevoix	**Canada**	**47.5 N**	**70.3 W**	**357**	**54**
Kara-Kul	**Tajikstan**	**39.0 N**	**73.5 E**	**5**	**52**
Siljan	**Sweden**	**61.0 N**	**14.9 E**	**368**	

- **52**Crater information from The New Solar System, Beatty et al., Cambridge, 1999.



CLEARWATERLAKES, CANADA

A FINAL THOUGHT

BEGINNING IN THE 1960'S, THE HUMAN SPECIES HAS HAD THE COPMBINED TECHNICAL AND ECONOMIC FOUNDATIONS TO REMOVE THE THREAT OF ITS EXTINCTION BY ASTEROID OR COMET IMPACT.

THE QUESTION REMAINS, WILL SOME ENTITY, NATION, OR GROUP OF NATIONS RE-MOBILIZE THIS CAPABILITY, A CAPABILITY THAT ALSO WOULD SERVE THE SPECIES IN MEETING MANY OTHER FUTURE CHALLENGES?

TERM PAPER TOPICS: 21

- **PRECIOUS METAL (AU, AG, PT, ETC.) CONCENTRATIONS IN IRON METEORITES AND THEIR POTENTIAL VALUE**
- **STATISTICAL THREAT OF AN ASTEROID OR COMET HITTING THE EARTH AS A FUNCTION OF MASS/SIZE**

TERM PAPER TOPICS: 20

- **ETHICS OF ACCEPTING INSUFFICIENT MANAGEMENT RESERVE**
- **HOW COULD THE APOLLO SYSTEMS HAVE BEEN USED AFTER APOLLO?**
- **FIRST LEVEL DESIGN COMPARISON OF BUSH INITIATIVE WITH APOLLO**
- **COMPARISON OF APOLLO MANAGEMENT WITH ONE OR MORE OF THE FOLLOWING: PANAMA CANAL, TRANSCONTINENTAL RAILROAD, INTERNATIONAL SPACE STATION, INTERSTATE HIGHWAY SYSTEM, SPACE SHUTTLE, TRANS-ALASKA PIPELINE**

TERM PAPER TOPICS: 19

- **MARTIAN RESOURCES IN THE "BILL OF MATERIALS" FOR <u>FIRST</u> PERMANENT MARTIAN HABITAT**
- **EARTH'S EXTREME LIFE ENVIRONMENTS THAT MAY BE FOUND ON MARS**
- **PROS AND CONS FOR EVIDENCE OF LIFE IN MARS METEORITE ALH84001**
- **√ MARS SURFACE RADIATION CONSIDERATIONS**

TERM PAPER TOPICS: 18

- **COMPARISON OF EVIDENCE FOR OLD AND YOUNG MARTIAN OCEANS**
- **SIGNIFICANCE OF VARIATIONS IN MARS OBLIQUITY**

TERM PAPER TOPICS: 17

- **EVIDENCE FOR AND AGAINST TWO DISTINCT COMPOSITIONS (IGNEOUS RESERVOIRS) IN THE MARTIAN MANTLE**
- **RESOURCE SIGNIFICANCE OF THINLY LAYERED ROCKS**

POSSIBLE TERM PAPER TOPICS: 10

- **GENERAL REVIEW OF He DISTRIBUTION IN APOLLO CORES**
- **REVIEW OF THEORY OF VOLATILE DEPOSITION IN PERMANENT SHADOW**

POSSIBLE TERM PAPER TOPICS: 9

- LUNAR MAGNETIC ANOMALIES
- VERY OLD TERRESTRIAL ZIRCONS
- NEPTUNE AND THE KUIPER BELT

POSSIBLE TERM PAPER TOPICS: 8

- **APPROACH TO CAPTURE MODELING**
- **COMPARISON OF ORANGE AND GREEN PYROCLASTIC GLASS CHEMICAL AND ISOTOPIC COMPOSITIONS**
- **SUMMARY OF ARGUMENTS FOR GIANT IMPACT ORIGIN OF THE MOON**
- **FACTORS LEADING TO WATER MIGRATION BACK INTO THE INNER SOLAR SYSTEM**

TERM PAPER TOPICS: 1/7

- **LECTURE 1**
  - **EARLY HISTORY OF THE SATURN V**
  - **TECHNICAL FOUNDATION FOR KENNEDY DECISION**
- **LECTURE 7**
  - **GALATIC HABITABLE ZONE**
  - **POSSIBLE CAUSES OF INNER SOLAR SYSTEM DEVOLATILIZATION**