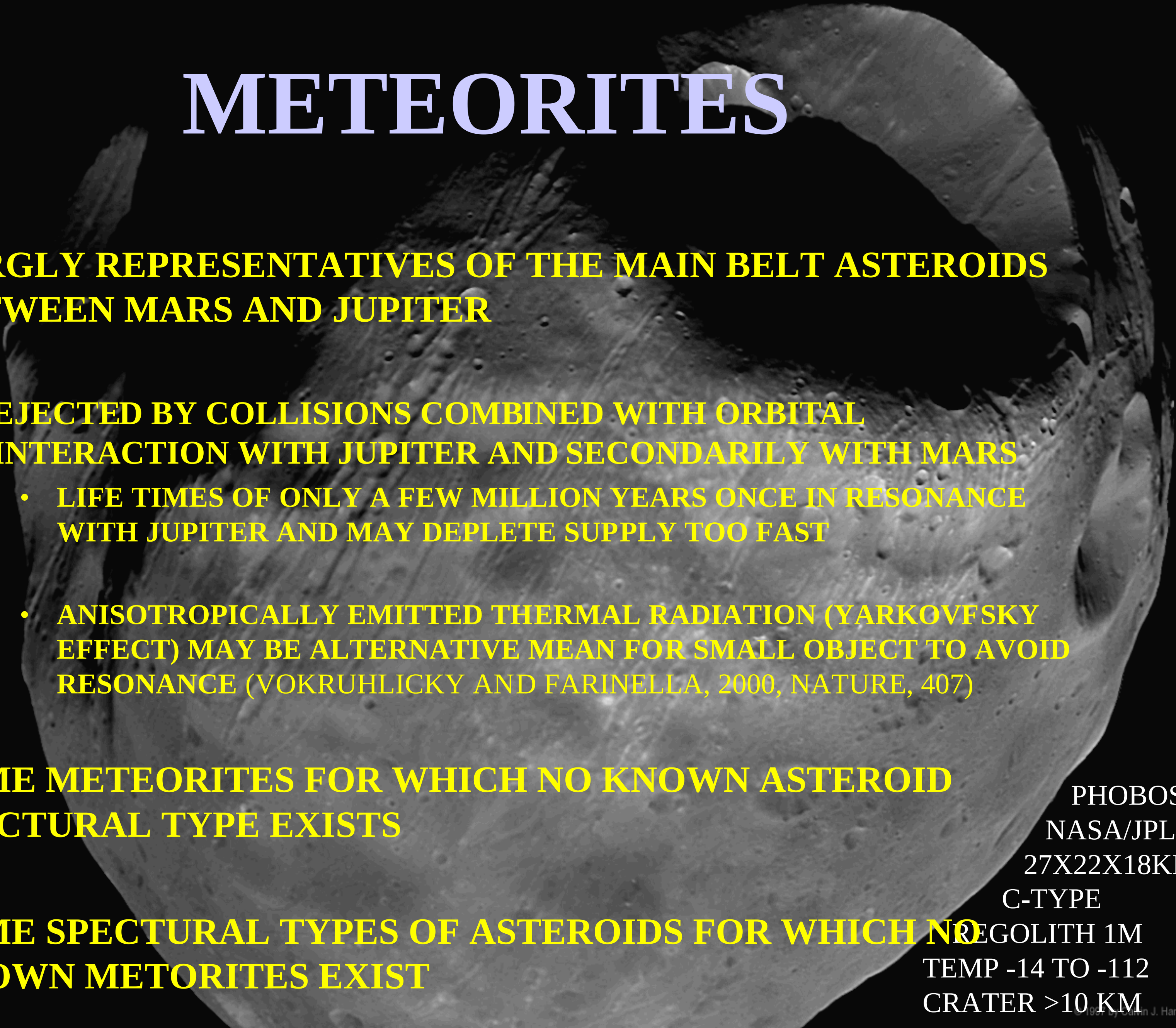
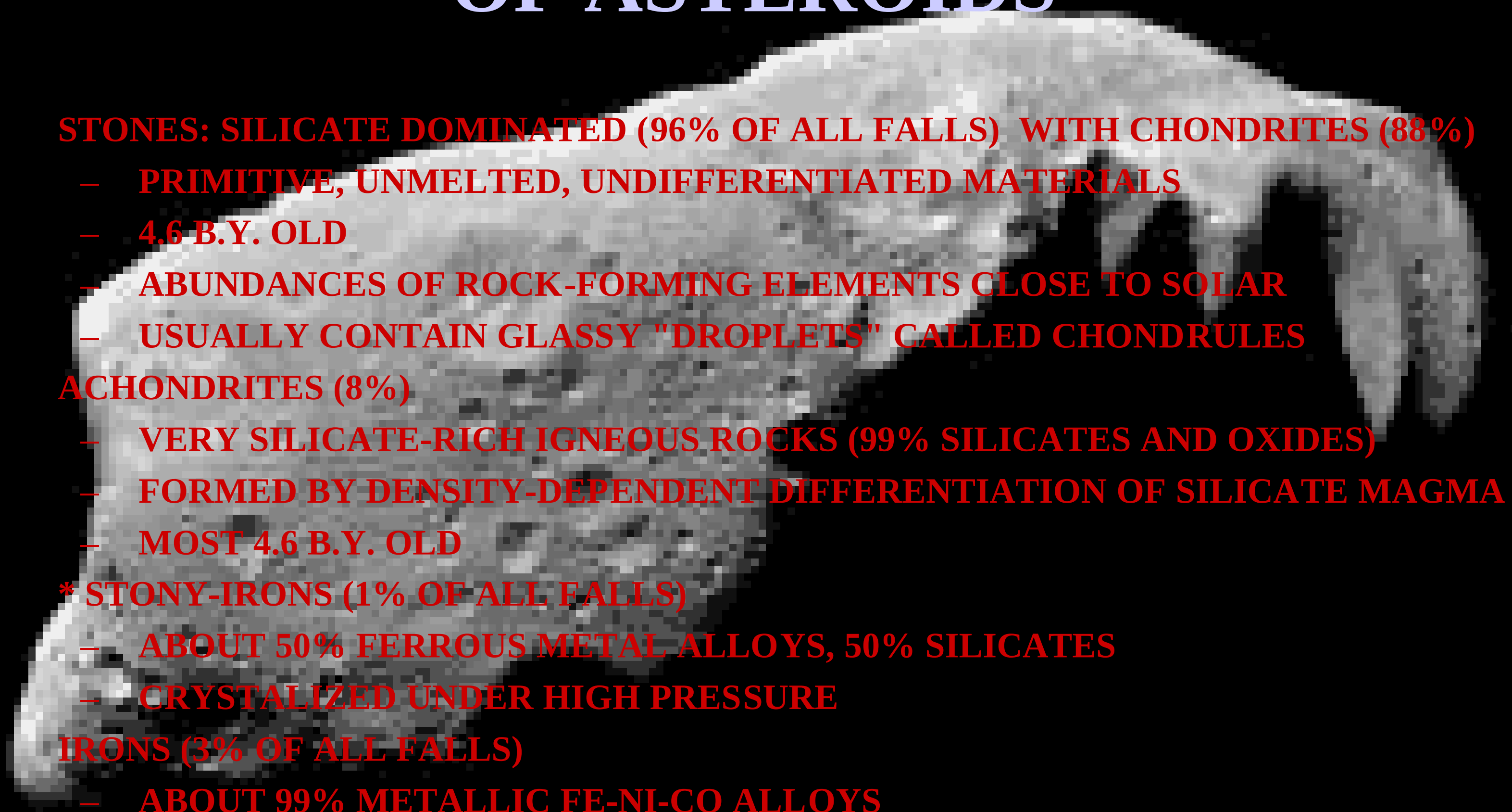
METEORITES

- **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

METEORITES AS REPRESENTATIVES OF ASTEROIDS



- STONES: SILICATE DOMINATED (96% OF ALL FALLS) WITH CHONDRITES (88%)
  - PRIMITIVE, UNMELTED, UNDIFFERENTIATED MATERIALS
  - 4.6 B.Y. OLD
  - ABUNDANCES OF ROCK-FORMING ELEMENTS CLOSE TO SOLAR
  - USUALLY CONTAIN GLASSY "DROPLETS" CALLED CHONDRULES
- ACHONDRITES (8%)
  - VERY SILICATE-RICH IGNEOUS ROCKS (99% SILICATES AND OXIDES)
  - FORMED BY DENSITY-DEPENDENT DIFFERENTIATION OF SILICATE MAGMA
  - MOST 4.6 B.Y. OLD
- * STONY-IRONS (1% OF ALL FALLS)
  - ABOUT 50% FERROUS METAL ALLOYS, 50% SILICATES
  - CRYSTALIZED UNDER HIGH PRESSURE
- IRONS (3% OF ALL FALLS)
  - ABOUT 99% METALLIC FE-NI-CO ALLOYS
  - INCLUSIONS OF FES, PHOSPHIDES, CARBIDES, GRAPHITE, SILICATES, DIAMONDS
  - APPARENTLY RELATED TO HIGH PRESSURE CRYSTALLIZATION

243 IDA
NASA/JPL
19X52 KM

METEORITE CHARACTERISTICS

- **STONES: SILICATE DOMINATED (96% OF ALL FALLS)**
- **CHONDRITES (88%)**
  - **PRIMITIVE, UNMELTED, UNDIFFERENTIATED MATERIALS RELATIVE TO SOLAR ABUNDANCES,**
  - **4.6 BY OLD**
  - **ABUNDANCES OF ROCK-FORMING ELEMENTS CLOSE TO SOLAR PROPORTIONS**
  - **USUALLY CONTAIN GLASSY "DROPLETS" CALLED CHONDRULES**
- **ACHONDRITES (8%)**
  - **VERY SILICATE-RICH IGNEOUS TEXTURED ROCKS (99% SILICATES AND OXIDES)**
  - **FORMED BY DENSITY-DEPENDENT DIFFERENTIATION, I.E., IN A GRAVITY FIELD**
  - **MOST 4.6 BY OLD**

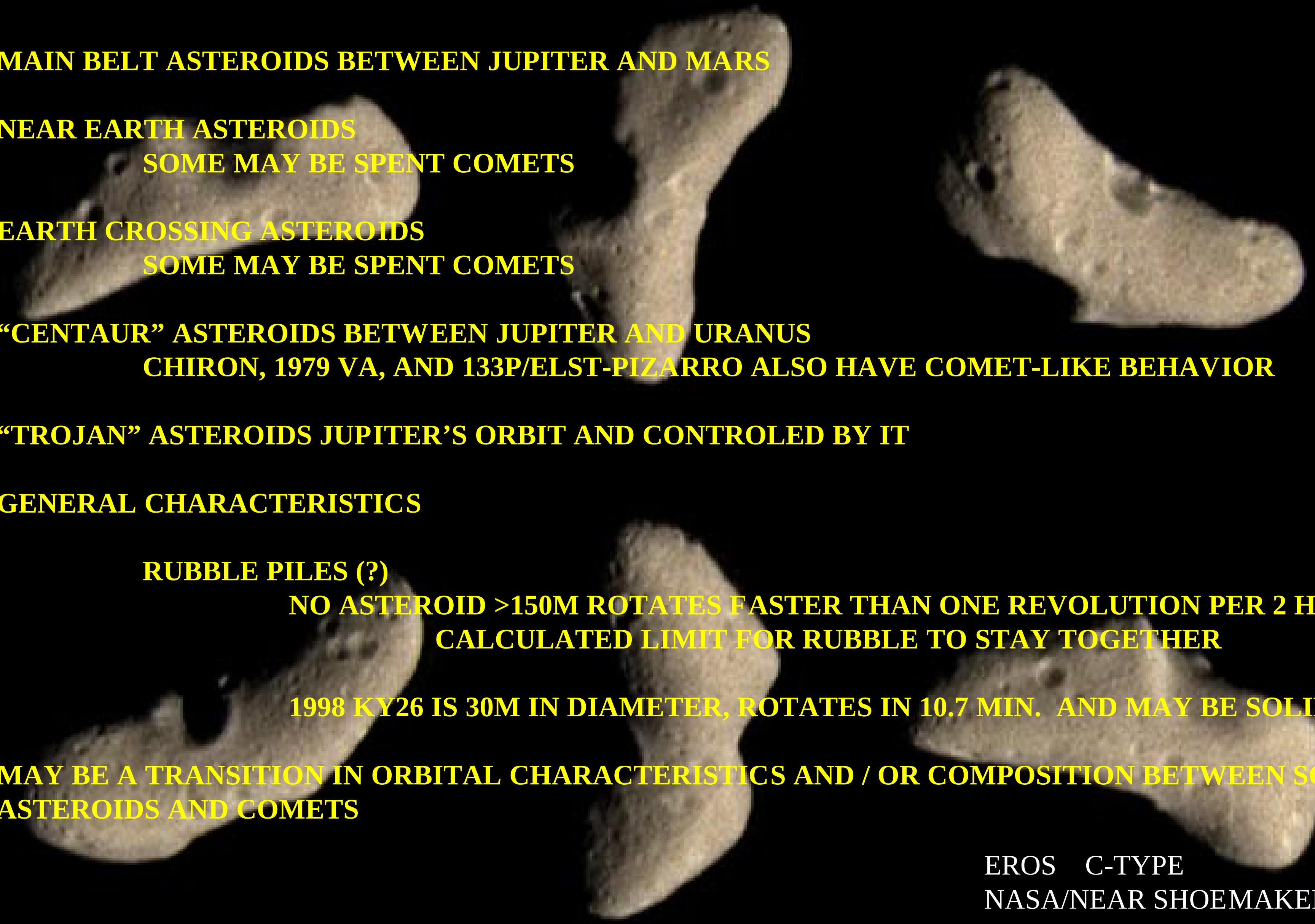
DEIMOS
NASA/JPL
15X12X11 KM
C-TYPE

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.
- 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.

GEOGRAPHOS
NASA/GOLDSTONE
~75X30KM

ASTEROIDS IN GENERAL



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 CONTROLED BY IT

GENERAL CHARACTERISTICS

RUBBLE PILES (?)

NO ASTEROID >150M ROTATES FASTER THAN ONE REVOLUTION PER 2 HOURS

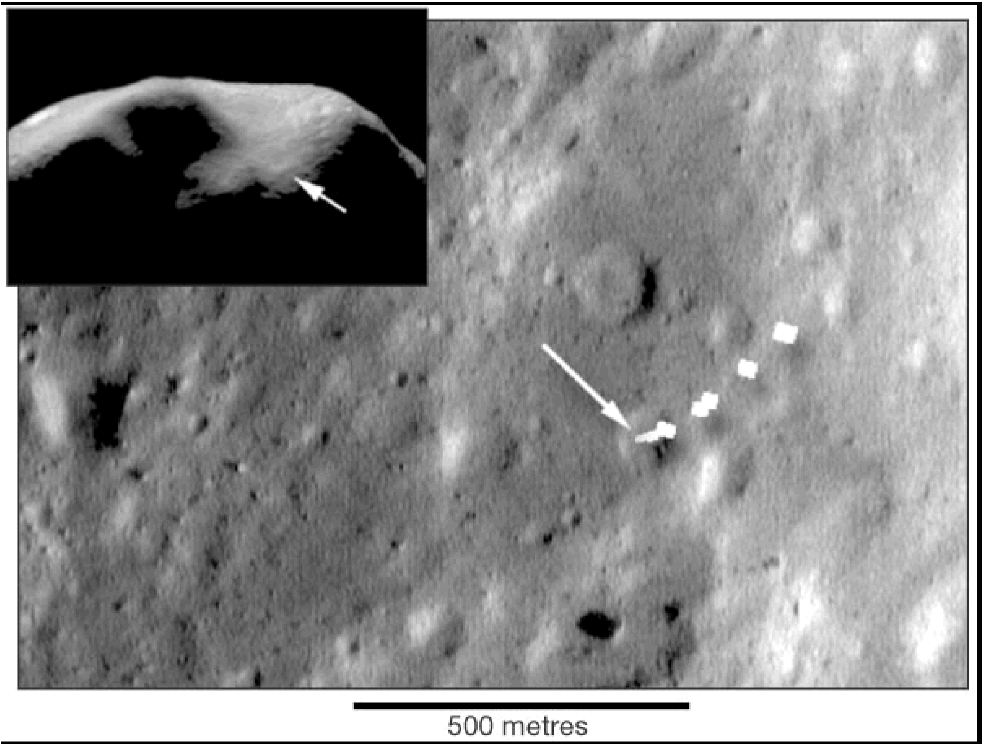
CALCULATED LIMIT FOR RUBBLE TO STAY TOGETHER

1998 KY26 IS 30M IN DIAMETER, ROTATES IN 10.7 MIN. AND MAY BE SOLID

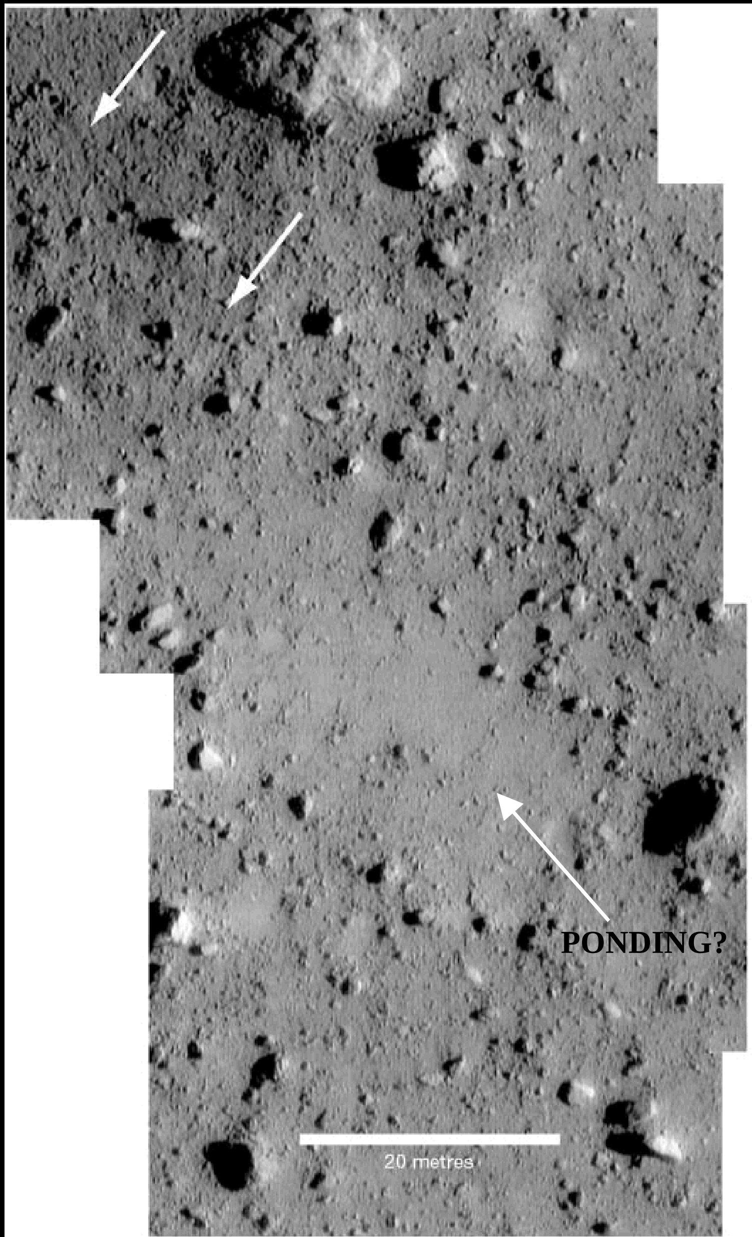
MAY BE A TRANSITION IN ORBITAL CHARACTERISTICS AND / OR COMPOSITION BETWEEN SOME ASTEROIDS AND COMETS

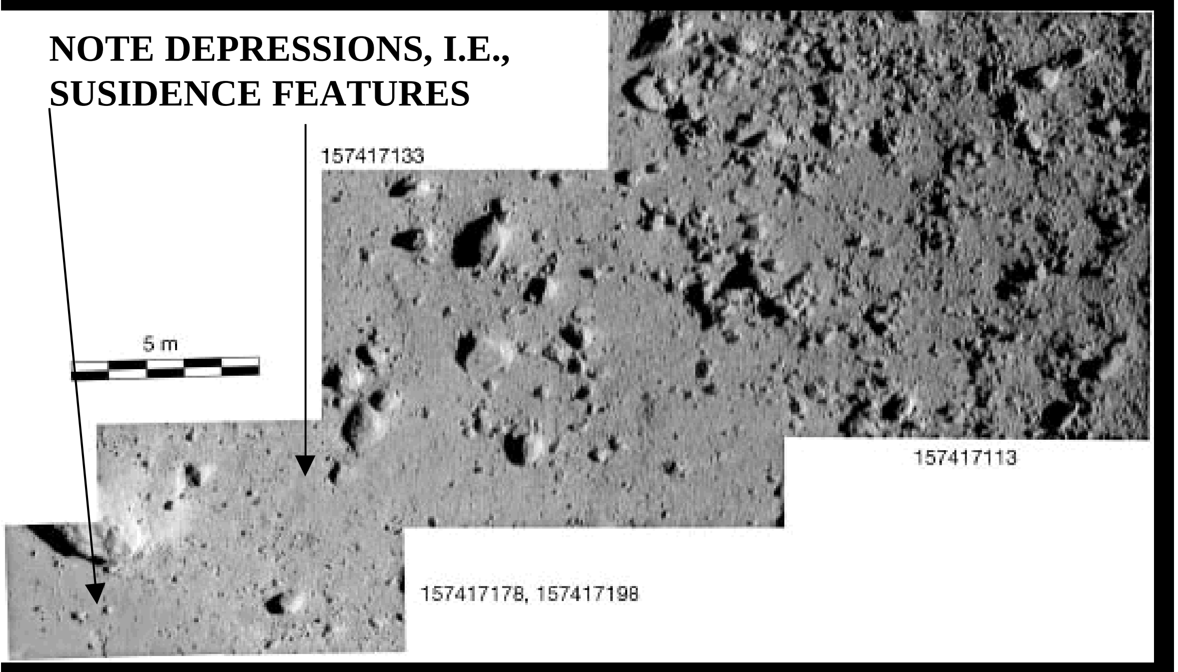
EROS C-TYPE
NASA/NEAR SHOEMAKER/APL
11X11X34 KM
1.3 GM/CM^3

EROS
FINAL DESCENT
NASA/NEAR SHOEMAKER/APL



GROVES

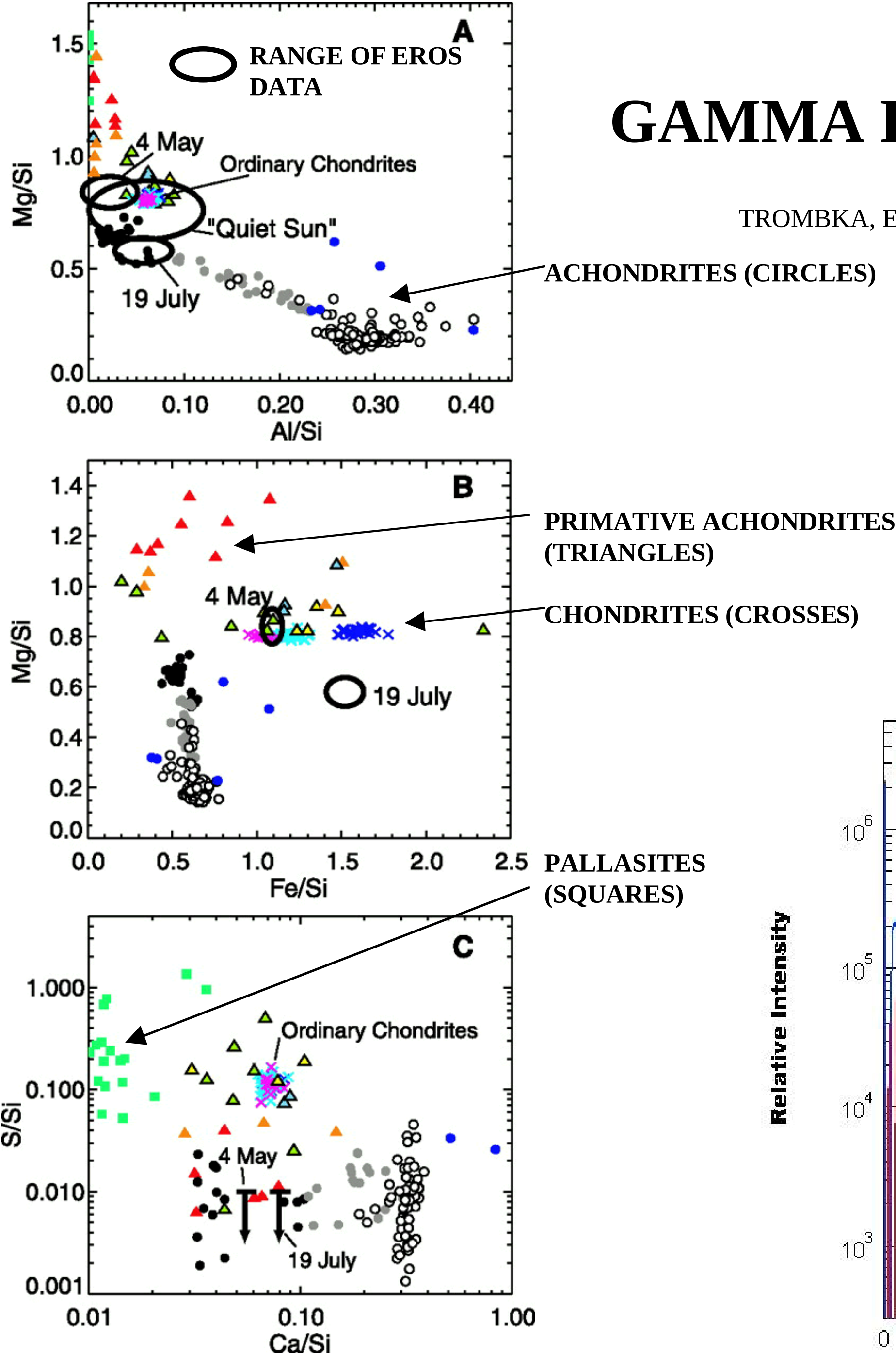


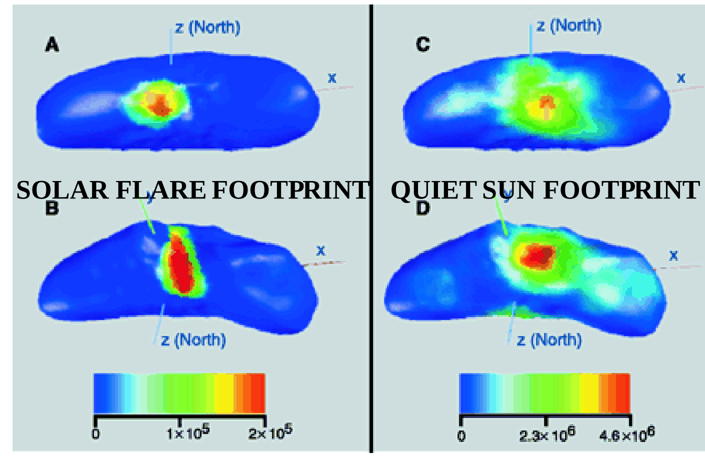


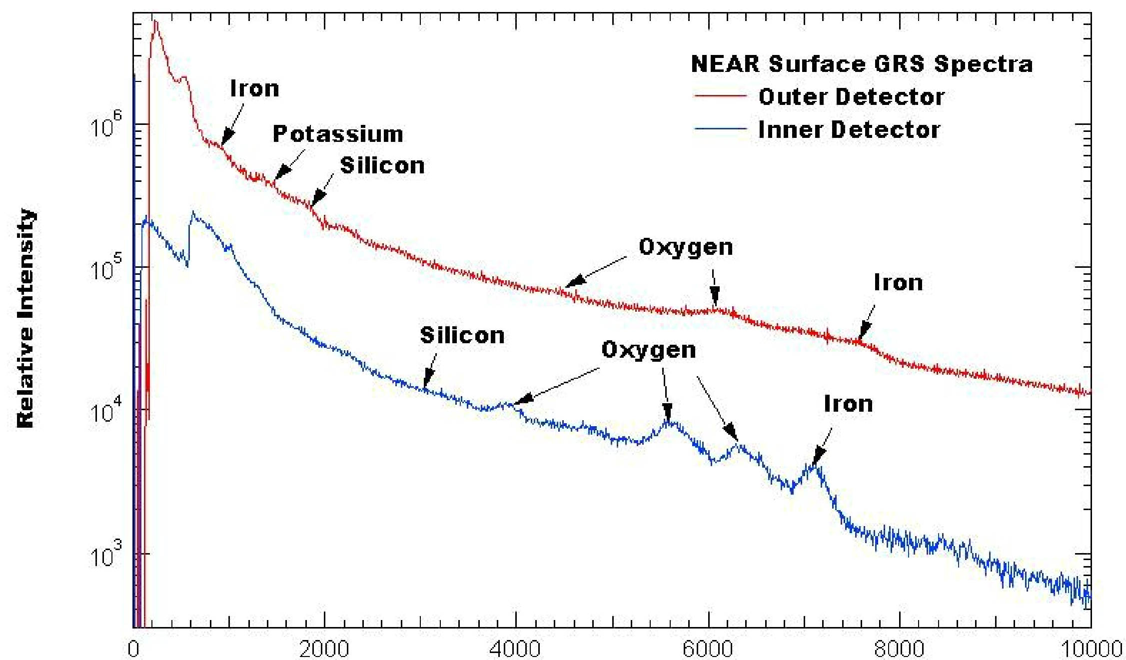
EROS
GAMMA RAY SPECTROMETER DATA

(UPPER ~ 10 CM OF MATERIAL)

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







NASA/NEAR SHOEMAKER/APL

SPACE WEATHERING

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

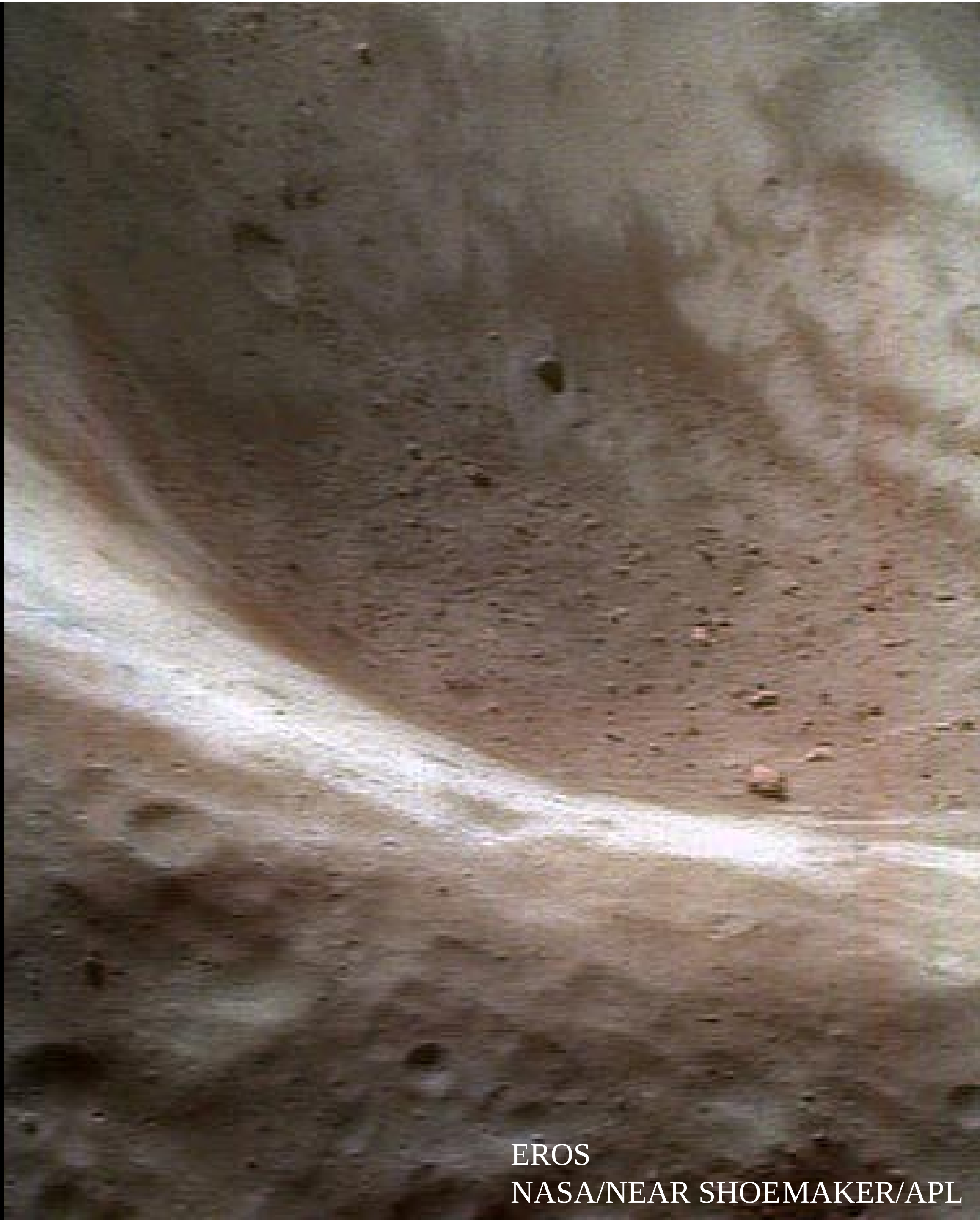
WEATHERING FACTORS:

<u>MICROMETEORS (PRODUCE NANO-PHASE IRON)</u>

SOLAR WIND/SOLAR FLARE IONS

GALACTIC COSMIC RAYS

COLD / HEAT

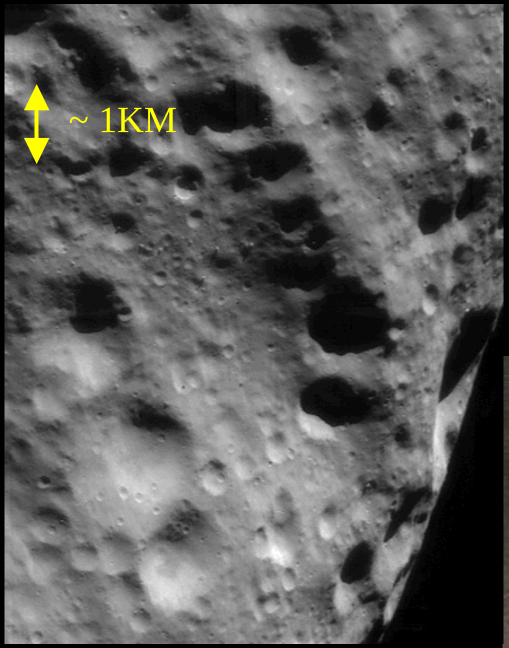


EROS
NASA/NEAR SHOEMAKER/APL

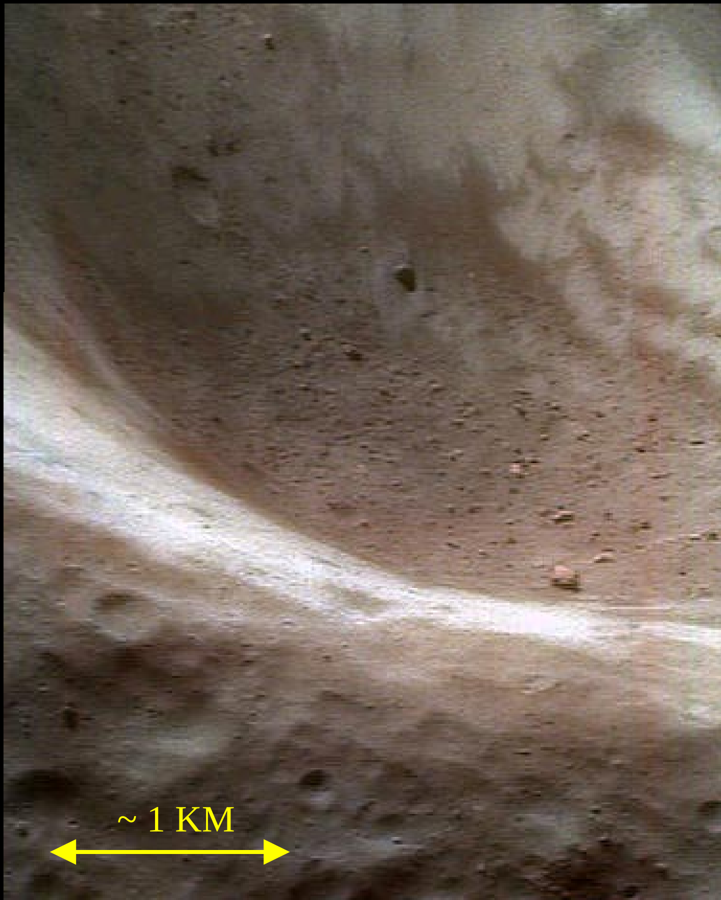
EROS

CLOSE-UPS AND COLOR

NASA/NEAR SHOEMAKER/APL



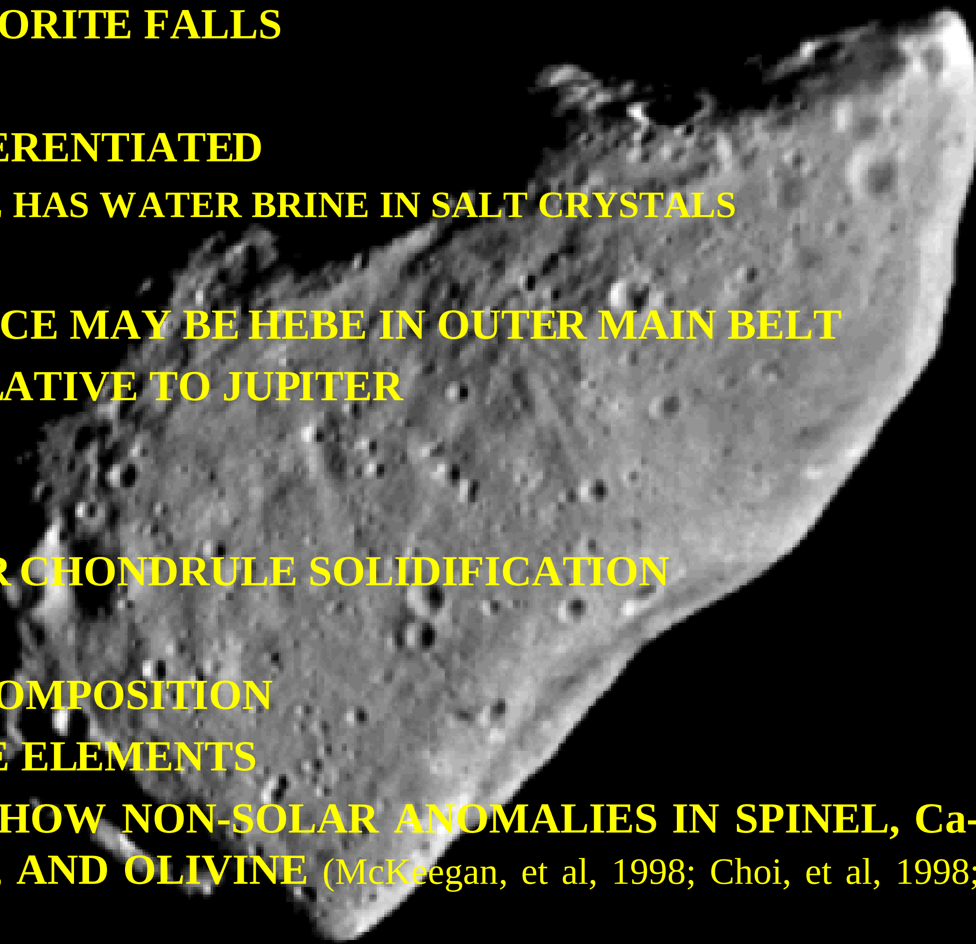
SADDLE



CHONDRITES

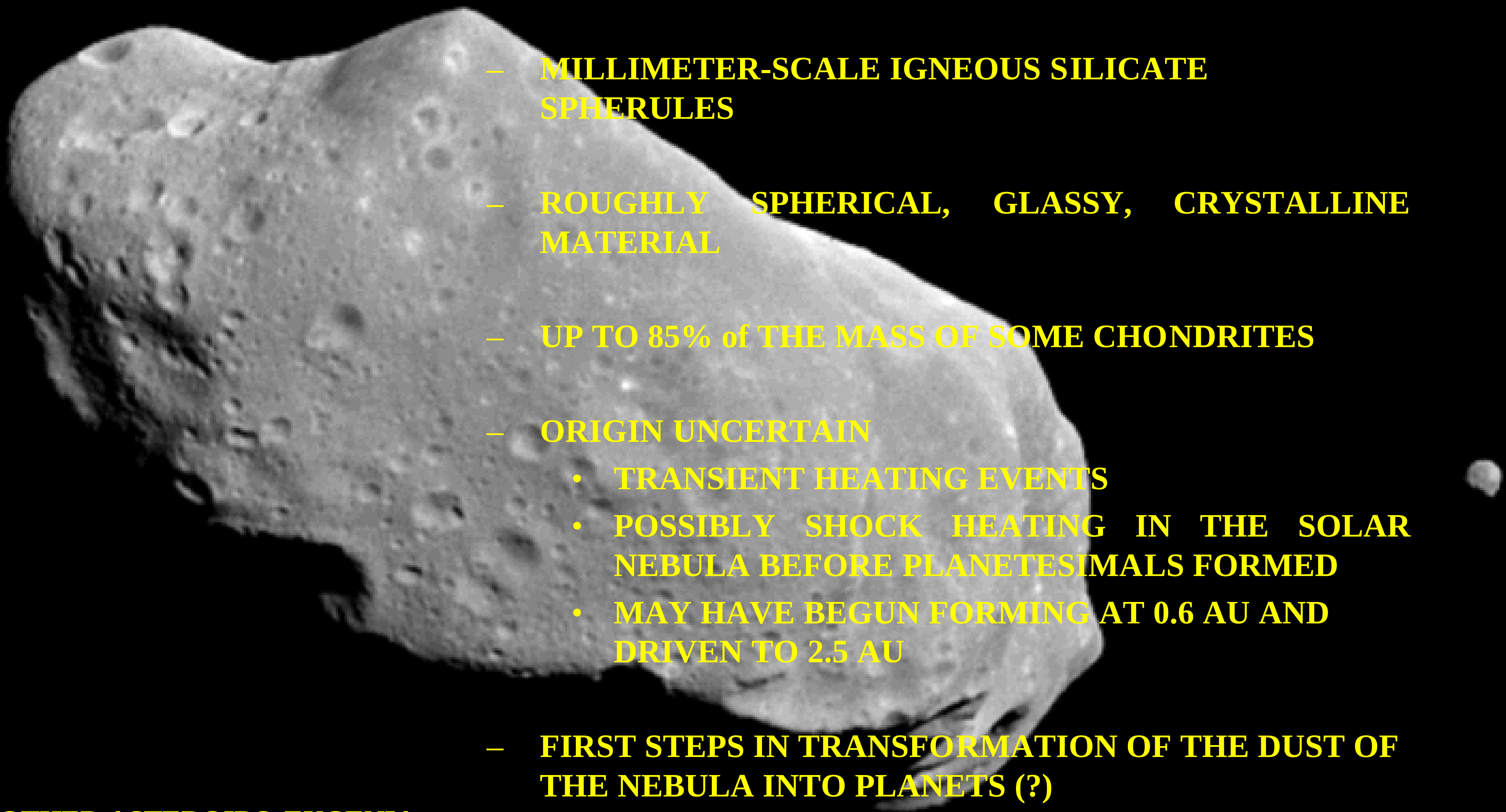
C-TYPE ASTEROIDS

- **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 SPHERULES
  - ROUGHLY SPHERICAL, GLASSY, 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 0.6 AU AND DRIVEN TO 2.5 AU
  - FIRST STEPS IN TRANSFORMATION OF THE DUST 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/CM^3

CHONDRITES -3

CHONDRULES CONTAIN "PRE-SOLAR" MATERIAL

(IDENTIFIED BY NON-SOLAR ISOTOPIC RATIOS)

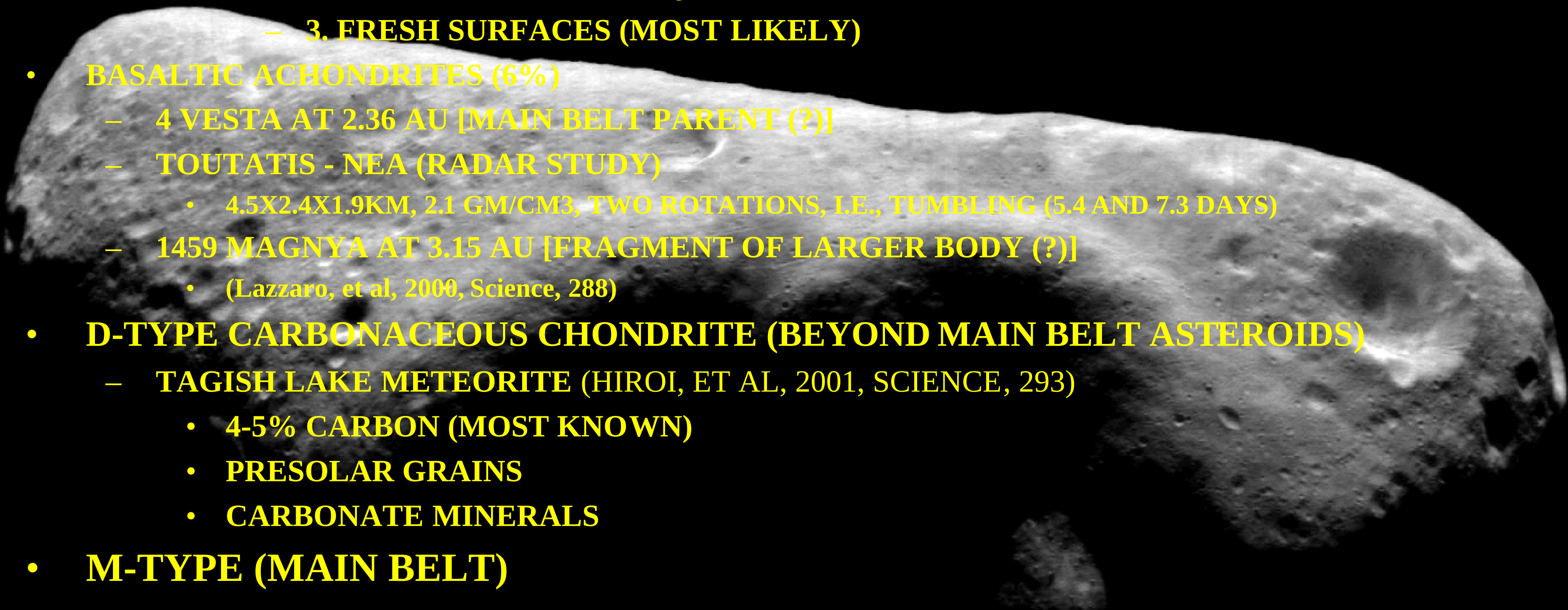
MOST ABUNDANT PRE-SOLAR MATERIAL YET IDENTIFIED

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

OTHER ASTEROIDS

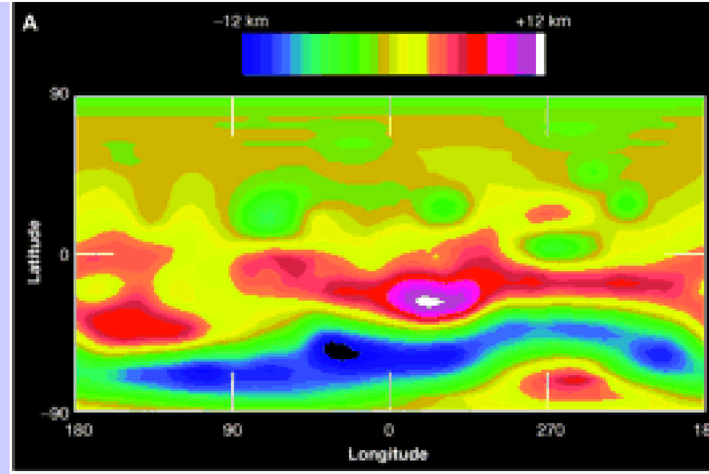
- S-TYPE
  - INNER ASTEROID BELT
  - EVIDENCE OF HEATING AND DIFFERENTIATION
  - 29 TELESCOPIC SPECTRA (Binzel, et al., 1996)
    - INTERMEDIATE BETWEEN S-TYPE AND ORDINARY CHONDRITES
      - 1. DISTINCT ROCK TYPES VS DIVERSE LARGER BODIES
      - 2. ABUNDANCE OF OPAQUE MATERIALS
      - 3. FRESH SURFACES (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)
- 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



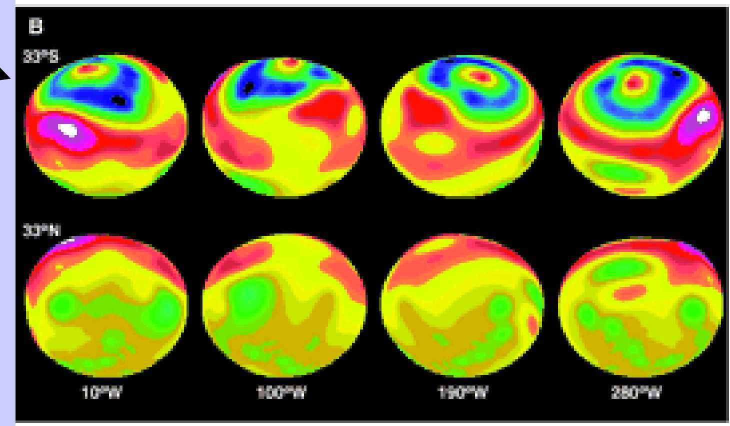
EROS
C-TYPE (REVISED BY GRS DATA)
11X11X33 KM
2.7 GM/CM^3
5.27 HR ROTATION
NASA/NEAR SHOEMAKER/APL

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)

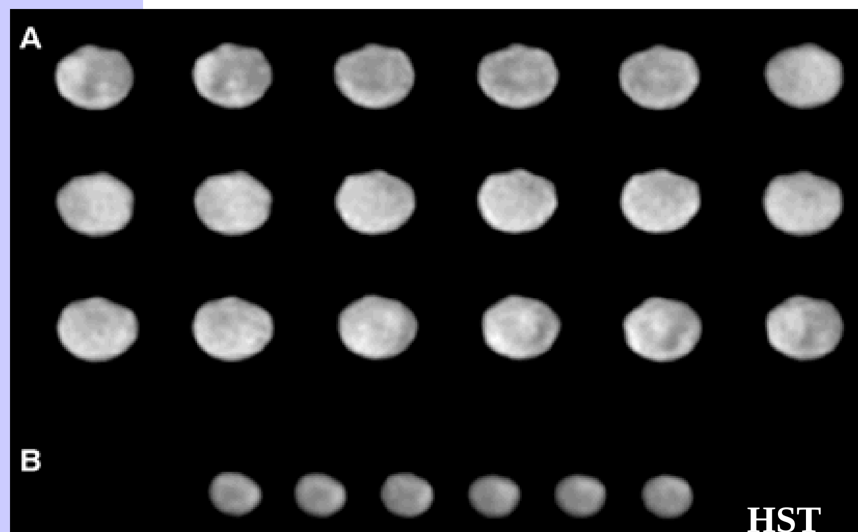
CRATERS FORM WITH DIAMETERS COMPARABLE TO ASTEROIDS MEAN RADIUS

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

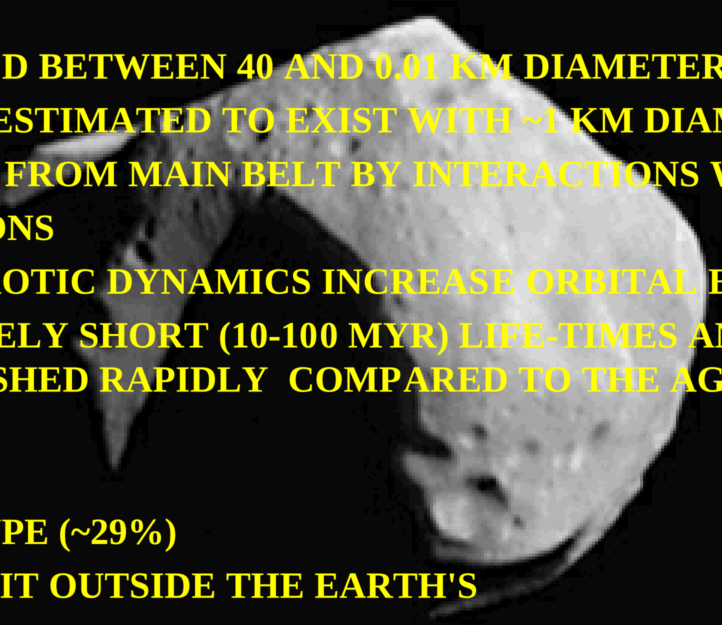


NEAR EARTH ASTEROIDS

- **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.**

    - **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

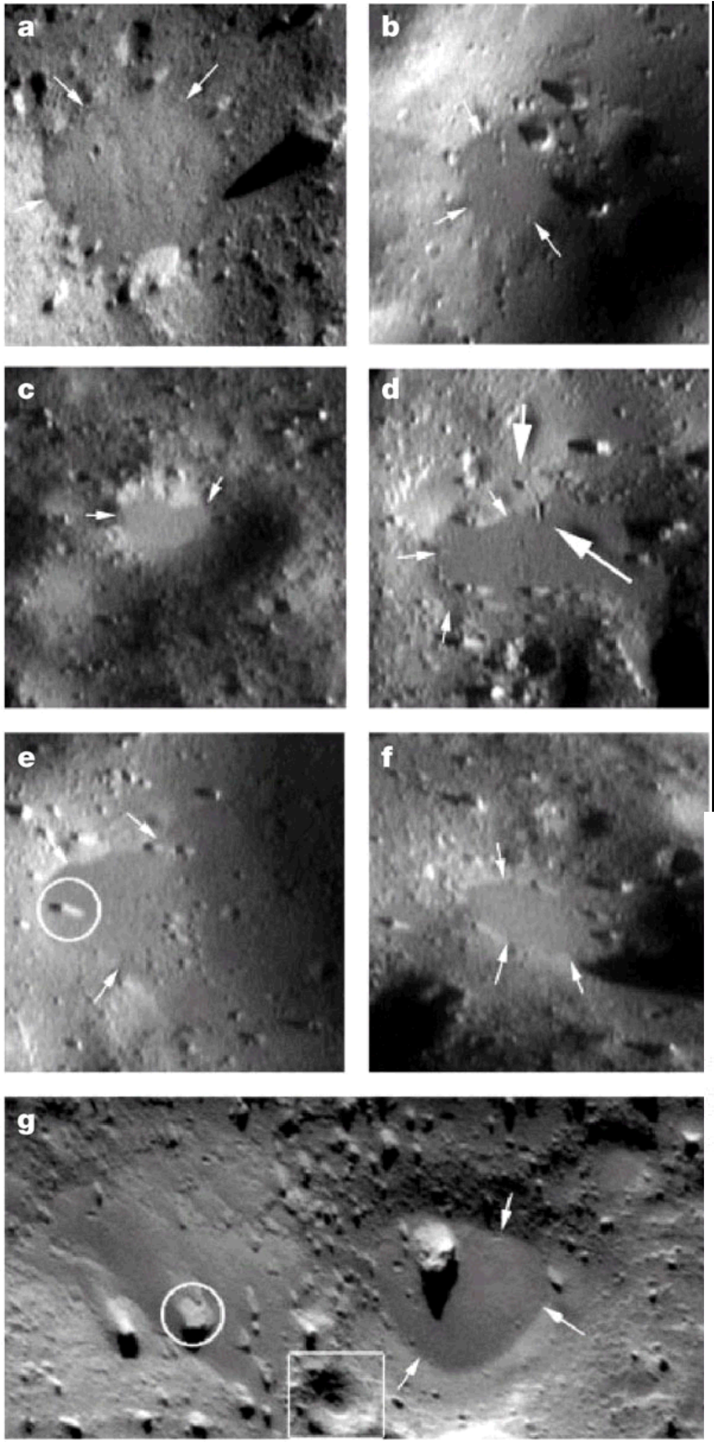
ASTEROID RESOURCES

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

SILICATE DOMINATED REGOLITH

EROS CLOSE-UP
NASA/APL

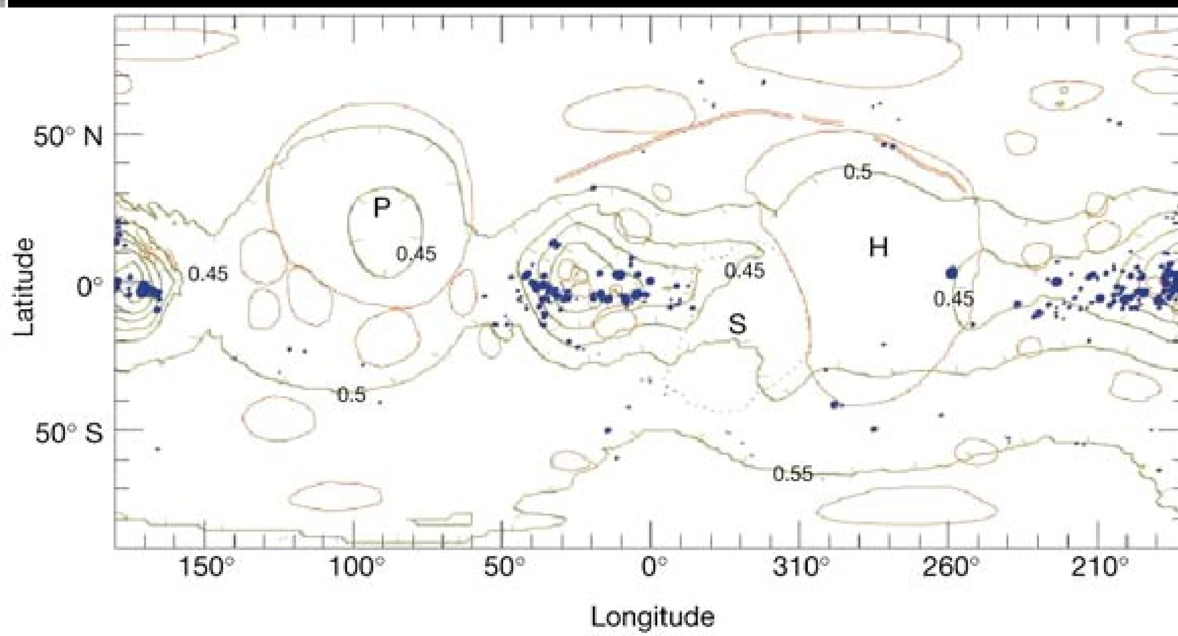
- **CHONDRITES (C-TYPE) AND ACHONDRITES**
  - **UNSORTED REGOLITH VERY SIMILAR TO THE MOON'S REGOLITH**
    - **SOLAR WIND VOLATILES**
    - **SOLAR WIND DERIVED VOLATILES**
    - **HYDROUS MINERALS**
    - **RADIATION PROTECTION MATERIALS**
- **EXAMPLES:**
  - **EROS [NEAR-EARTH, C-TYPE ASTEROID]** (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

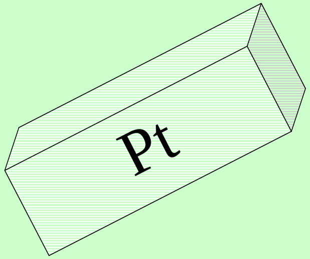
DORMANT COMETS

- **HYDROCARBON / DUST CRUST (?)**

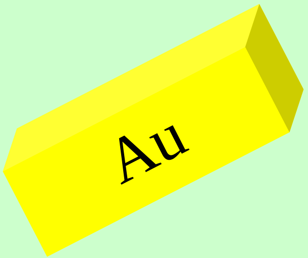
- **ICE-RICH BENEATH CRUST**
  - **WATER, HYDROGEN, OXYGEN**

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 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**
  - **FIRST 100KG HELIUM-3 SHIPMENT TODAY WORTH ~$500 MILLION**

ASTEROID RESOURCES SELECTED REFERENCES

- **LEWIS, ET AL, 1993, RESOURCES OF NEAR EARTH SPACE, 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**