BEGINNING OF THE SOLAR SYSTEM

A MODEL IN-WORK

NEEP 533: Lecture 7
Harrison H. Schmitt
LONG PERIOD COMETS

SHORT PERIOD COMETS

CALTECH, 1/14/03: http://voyager.jpl.nasa.gov/mission/didyouknow.html
MAJOR STAGES

- PRE-NEBULA MOLECULAR CLOUD
- SOLAR NEBULAR EVOLUTION
  - LAPLACE 1787
- FORMATION OF GAS GIANTS
- INNER SYSTEM ACCRETION

GENERAL SOURCES: TAYLOR, 2001; CANUP AND RIGHTER, 2000; WASSERBERG, 2000;
COSMO-PHYSICAL RULES

• CONSERVATION OF ANGULAR MOMENTUM
  – ACCRETION INCREASES ORBITAL VELOCITY

• LOSS OF ANGULAR MOMENTUM THROUGH DRAG BY GAS AND DUST
  – REDUCES ORBITAL VELOCITY

• TEMPERATURE GRADIENT TOWARD SUN
  – VERY STEEP WITHIN 4-5 AU
ASTRONOMICAL OBSERVATIONS

• MOLECULAR CLOUDS
  – UV RADIATION SIMPLIFIES ORGANICS

• AGB STARS (ASYMPTOTIC GIANT BRANCH)
  – s-process synthesis

• TYPE II SUPERNOVAS
  – r-process synthesis

• MAIN SEQUENCE STAR FORMATION
  – SUN-LIKE, SINGLE STARS EXIST
  – T-TAU RI EVENTS EXIST
  – FU-ORIONIS EVENTS EXIST
COSMO-ISOTOPIC CLOCKS

PARENT/DAUGHTER

- ALUMINUM-26 / MAGNESIUM-26
- POTASSIUM-40 / ARGON-40 & CALCIUM-40
- CALCIUM-41 / POTASSIUM-41
- MANGANESE-53 / CHROMIUM-53
- IRON-60 / NICKEL-60
- RUBIDIUM-87 / STRONTIUM-87
- LEAD-107 / SILVER-107
- IODINE-129 / XENON-129
- SUMARIUM-146 / NIODENIUM-142
- SUMARIUM-147 / NIODENIUM-143
- LUTICIUM-176 / HAFNIUM-176
- HAFNIUM-182 / TUNGSTEN-182
- REHNEIUM-187 / OSMIUM-187
- PLATINUM-190 / OSMIUM-186
- THORIUM-232 / LEAD-208
- URANIUM-235 / LEAD-207
- URANIUM-238 / LEAD-206
- PLUTONIUM-244 / FISSION XE

HALF-LIFE (10^6 YR.)

- 0.73
- 1270
- 1
- 3.7
- 1.5
- 48,800
- 5.5
- 15.7
- 103
- 106,000
- 35,700
- 9
- 41,600
- 450,000
- 14,010
- 704
- 4469
- 80

RED CURRENTLY MOST USEFUL
“4.6 BILLION YEARS AGO, IN A MOLECULAR HYDROGEN CLOUD, IN A SPIRAL GALAXY FAR AWAY, OUR SUN WAS BORN.”

NASA HUBBLE SPACE TELESCOPE
MOLECULAR CLOUD

EAGLE NEBULA

ORION NEBULA
PRE-NEBULA MOLECULAR CLOUD - 1

- MODEL OF HABITABLE ZONE OF THE MILKY WAY GALAXY (GONZALES, ET AL, 2004; LINEWEAVER, ET AL, 2004)
  - 7-9 PARSECS FROM GALACTIC CENTER
  - SIZE OF ZONE IS FUNCTION OF TIME SINCE GALAXY FORMATION AND DISTANCE FROM CENTER
    - WIDENS WITH TIME AND ELIMINATION OF “TIME TO LIFE” OF 4±1 BILLION YEARS
  - STARS FORMED 4-8 BILLION YEARS AGO
    - 75% OLDER THAN SUN (4.6 BILLION YEARS)
  - PROBLEMS WITH OTHER REGIONS
    - EARLY AND NEAR GALACTIC CENTER: TOO MANY SUPERNOVAE
    - >9 PARSECS: TOO METAL POOR
PRE-NEBULA MOLECULAR CLOUD - 2

- HYDROGEN
  - \(10^2 - 10^6 \text{ H}_2/\text{cm}^3\)

- SILICATE DUST
  - OLIVINE AND PYROXENE (\(\text{Mg/Fe} > 0.9\))

- METAL + METAL SULFIDE DUST

- SIMPLE ORGANIC MOLECULES

- CARBON
  - AMORPHOUS
  - DIAMOND
  - SILICON CARBIDE

- STEADY STATE INTRODUCTION OF EXTINCT ISOTOPES
  - AGB STARS AND SUPERNOVAE
    - ~50/50 CONTRIBUTORS
PRE-NEBULA MOLECULAR CLOUD - 3

- PRE-SOLAR NEBULA “FUN” CAIs ($T_0$ MINUS 2-3 M. Y.; Pb-Pb AGE)
  - $^{41}$K ($^{41}$Ca DAUGHTER / 0.1 M.Y. HALF-LIFE)
  - OTHER ISOTOPIC ANOMALIES CONSISTENT WITH SUPERNOVA PROCESSES

- CRITICAL FACTORS FOR US IN SEPARATION OF SUB-CLOUD
  - $\leq$ 2 SOLAR MASSES
  - ADEQUATE DENSITY
  - LOW ANGULAR MOMENTUM (ROTATION RATE)
  - ISOLATION FROM OTHER STAR FORMATION

CAI = CALCICUM-ALUMINUM INCLUSIONS IN METEORITES: HIGH TEMPERATURE CRYSTALLIZATION, REFRACTORY MINERALS “FUN” = FRACTIONATION AND UNKNOWN NUCLEAR
PRE-NEBULA MOLECULAR CLOUD - 5

• TRIGGER FOR GRAVITATIONAL COLLAPSE OF SUB-CLOUD ($T_0$ MINUS ~0.15 M.Y.)
  – GRAVITATIONAL WAVES IN GALAXY ?
  – SUPERNova SHock WAVE ?
  – GLOBULAR CLUSTER IMPACT ON GALAXY ?

• RAPID SUB-CLOUD COLLAPSE AND HEATING
  – INCREASINGLY RAPID ROTATION
  – SPIRAL DISK ~30 AU IN RADIUS
  – EARLY FORMATION OF PROTO-SUN

• IN-FALL FROM PARENT CLOUD
  – NEBULAR SHock FRONTS ABOVE AND BELOW ECLIPTIC
MILKY WAY
SUPERNova

1987A SUPERNova

AFTER
BEFORE
EARLY NEBULAR EVOLUTION - 1

- SPIRAL STRUCTURE OF NEBULA
  - MOMENTUM TRANSFER OUTWARD DURING MASS FLOW INWARD

- CONDENSATION OF CARBONACEOUS MATRIX OF CI CHONDRITES IN OUTER NEBULA

- SULFIDE AND FE-RICH METAL CONCENTRATION IN ECLIPTIC
  - LARGELY ABSENT DURING CHONDRULE FORMATION

- RAPID COOLING OF OUTER NEBULA
  - HELIOCENTRIC TEMPERATURE GRADIENT 50-1800° C
  - PROGRESSIVELY INWARD EVAPORATION OF DUST PARTICLES
Meanwhile, what are carbonaceous chondrites?
EARLY NEBULAR EVOLUTION - 2

- VOLATILE ELEMENT DEPLETION IN INNER SOLAR SYSTEM RELATIVE TO SOLAR AND PRIMITIVE CARBONACEOUS CHONDRITE COMPOSITIONS
  - SEEN IN Rb RELATIVE TO Sr AS WELL AS OTHER ELEMENTS
  - BEFORE CAI OR CONDRULE FORMATION
  - DUST SELECTIVELY VAPORIZED AS IT FLOWED THROUGH NEBULAR SHOCK FRONTS AND UP TEMPERATURE GRADIENT?
    - RECYCLED BY BI-POLAR JETS BACK INTO NEBULA?
  - AMOUNT OF DEPLETION APPEARS TO BE HELIOCENTRIC
    - HOMOGENIZATION INCOMPLETE

- EMBRYONIC SUN FORMATION
  - D BURNING AT ~0.013 SOLAR MASS (13 JUPITER MASSES)
    - INTERNAL CONVECTION STARTS
  - EARLY HYDROGEN (PROTON) BURNING AT 0.075
  - BI-POLAR SOLAR WIND JETS (T-TAURI STAGE)
    - MOMENTUM DISSIPATION BY ~1 SOLAR MASS TRANSFER TO BACK TO MOLECULAR CLOUD
PRE-$T_0$ DEVOLATILIZATION

ELEMENT ABUNDANCES FOR CV3 CARBONACEOUS CHRONDRITES (NORMALIZED TO CI AND Si)

NOTE: LITTLE CORRELATION WITH GEOCHEMICAL PARAMETERS, SUCH AS SIDEROPHILE, LITHOPHILE, OR CHALCOPHILE AFFINITIES JUST VOLATILITY. FURTHER, NO ASSOCIATED ISOTOPIC FRACTIONATION

SIDEROPHILE: GOES WITH IRON LITHOPHILE: GOES WITH SILICATES CHALCOPHILE: GOES WITH SULFUR

CONDENSATION TEMPERATURE (K) AT $10^{-4}$ BAR

LOW VOLATILITY

MODERATELY VOLATILE

HIGHLY VOLATILE
NEBULAR DYNAMICS AT $T_0 \pm 50,000$ YEARS

- CI MATRIX CONDENSATION
- $\sim 1800K$ MOLECULAR CLOUD
- SHOCK FRONTS
- SUN @ $>0.3M$
- $\sim 50K$ MOLECULAR CLOUD

- X-WIND
- DUST/GAS FLOW
- BI-POLAR JETS
- MOMENTUM LOSS
- SPIRAL MOMENTUM LOSS
- ECLIPTIC METAL
FU ORIONIS GAS CLEARLING EVENTS

FU ORIONIS

GAS?

“SNOW LINE”?

V1515 Cgy
CAUSE OF DEVOLATILIZATION WITHOUT ISOTOPIC FRACTIONATION

- SOLAR ACTIVITY CLEARED ELEMENTS Whose Condensation Temperatures Are Less Than About 1000º K
- NEITHER EVAPORATION OR CONDENSATION OF DUST GRAINS MATCHES DATA
- RELEASE OF VOLATILE ELEMENTS BASED ON REFRACTIVITY OF HOST MINERALS APPEARS TO MATCH DATA BEST
  - CRYSTALLINE DUST MAY HAVE MOVED FROM THE MOLECULAR CLOUD AND THROUGH NEBULAR SHOCK FRONTS, MIGRATING DUE TO DRAG UP THE TEMPERATURE GRADIENT TOWARD THE SUN.
EARLY NEBULAR EVOLUTION - 3A

- CAI FORMATION (\( T_0 = 4566 \pm 2 \) M.Y. ago)
  - LEAD-LEAD AGE
  - FINE GRAINED CAIs ARE VERY HIGH TEMPERATURE CONDENSATES
    - COURSER GRAINED CAIs ARE EVAPORATION RESIDUES
    - COMPLEXITY IDICATES MULTI-STAGE PROCESSING
  - PREDOMINENTLY IN CO, CV, CM CARBONACEOUS CHONDrites
  - RARELY FOUND ENCLOSED IN CHONDRULES
  - OXYGEN ISOTOPE RATIOS UNIFORM, I.E., COMMON SOURCE
    - \(^{16}\text{O} \) MUCH HIGHER THAN OTHER METEORITES
EARLY NEBULAR EVOLUTION - 3B

• ACCRETION OF CENTIMETER Sized DUST BALLS
  – TURBULENT / GASEOUS ENVIRONMENT (10^{-4} - 10^{-6} TORR)
  – COLLISIONS AND STICKING OF DUST PARTICLES
  • ELECTROSTATIC FORCES IN STRONG MAGNETIC FIELDS ?
NEBULAR EVOLUTION - 3C
FORMATION OF GAS GIANTS

• ACCRETION OF FOUR OUTER SYSTEM ROCKY PLANETESIMALS
  – 10-15 EARTH MASSES

• GAS CLEARING EVENT NEAR $T_0$
  – “SNOW-LINE” AT ~5 AU

• JUPITER+SATURN WINS GAS ACCRETION BATTLE ($\sim T_0 + 0.05$ M.Y.)
  – JUPITER FORMS COMETARY SCREEN FOR INNER SYSTEM
    • ESTIMATED 1000 X REDUCTION IN COMETARY IMPACTS ON EARTH

• NEPTUNE AND URANUS BECOME ICE GIANTS

• REMAINING ICES FORM KUIPER BELT OBJECTS OUTSIDE NEPTUNE
  – INTERACTION WITH GIANTS DISTRIBUTE KUIPER OBJECTS INWARD
    (SHORT PERIOD COMETS) AND OUTWARD (ÖORT CLOUD AND LONG
    PERIOD COMETS)
EARLY NEBULAR EVOLUTION - 4

• CHONDRULE FORMATION ($T_0 + 2-4$ M.Y.; $^{26}$Al, $^{53}$Mn)
  – AFTER MOST OR ALL CAIs FORMED
    • SOME APPEAR TO BE REMELTED CAIs
  – AFTER GAS CLEARING EVENT AND GAS/ICE GIANT FORMATION
  – CRYSTALIZATION FROM FLASH MELTING OF CENTIMETER Sized DUST PARTICLES
    • RAPID COOLING IN NEBULA FROM 1750-2150K
  – OXYGEN ISOTOPE RATIOS HIGHLY VARIABLE
    • VARIABLE FRACTIONATION OR NO COMMON SOURCE

• CHONDRULE RE-PROCESSING
  – MULTIPLE FLASH HEATING CYCLES
EARLY NEBULAR EVOLUTION - 5
OUTER AND MID NEBULA

- SUN’S ARRIVAL ON MAIN SEQUENCE EVOLUTION
  - SUN’S GROWTH STOPPED WHEN OUTFLOW = INFLOW
  - SOURCE MATERIAL IN NEAR-BY CLOUD DEPLETED
STAGES OF SOLAR SYSTEM EVOLUTION

$T_0 \pm ~100,000$ YEARS

1. COLLAPSE INITIATED
   - Spiral structure established
   - Metal to Ecliptic
   - Matrix material condensed

2. ACCELERATION OF INFALL
   - Devolatilizat’、“n process
   - D burning begins at 0.013 M
   - H burning begins at 0.075 M

3. BI-POLAR JETS
   - CAIs FORM
   - OUTER PLANET CORES FORM
   - Gas clearing event (S)
   - Gas / Ice giants and Kuiper objects form

4. FLASH HEATING OF DUST BALLS
   - CHONDRITES FORM
   - WATER-ICE MIGRATION INWARD

5. SUN ENTERS MAIN SEQUENCE
   - Early mid-nebula accretion
EARLY MID-NEBULAR EVENTS

- CHONDRULE AGGREGATION WITH FE-RICH METAL INTO ASTEROID BELT PLANETESIMALS
  - 100-500 KM SIZE BODIES
  - JUPITER PREVENTS ACCRETION OF PLANET IN ASTEROID BELT

- PLANETESIMAL PARTIAL MELTING AND DIFFERENTIATION (2-4 M.Y. $^{107}$Pb, $^{26}$Al)
  - $^{26}$Al DECAY HEATING ONLY WITHIN ~3 M.Y.
  - CHONDRITE METAMORPHISM

- PLANETESIMAL FRAGMENTATION AND RE-AGGREGATION
  - ORIGIN OF CHONDRITE BRECCIAS AS METEORITES

BRECCIA: ROCK MADE UP OF FRAGMENTS OF OTHER ROCKS
BEGINNING

STATUS OF CURRENT UNDERSTANDING

MOLECULAR CLOUD AGGREGATION (AGB / SUPERNova NUCLEOSYNTHESIS)
- “FUn” CAI CONDENSATION ($T_0$ - ~ 2 M. Y.)
- SOLAR SUB-CLOUD SEPARATION AND COLLAPSE (SN TRIGGER / $T_0$ - < 750 K.Y. [$^{41}$Ca])
- SOLAR NEBULa FORMATION FROM MOLECULAR CLOUD+DUST
- VOLATILE ELEMENT DEPLETION (PARTIAL CONDENSATION/T-Tauri)
- OUTER NEBULa COOLED

$T_0$’
- CAI FORMATION NEAR SUN (CONDENSATION AND MELTING >1800K [Pb])
- CM-SIZED DUST BALL AGGREGATION / METAL-SULFIDE SEPARATION (GRAVITY)
- FLASH HEATING EVENTS / CHONDRULE FORMATION / T-Tauri / META’ISM
- GAS CLEARING INNER/CONDENSATION OUTER SOLAR SYSTEM

> 5AU
- ROCK / ICE PROTOPLANET ACCRETION - OUTER SOLAR SYSTEM
- JUPITER / SATURN / URANUS / NEPTUNE / KUIPER OBJECT ACCRETION
- NEBULa TURBuLENCe

~3AU
- M-KM SIZED ASTEROID ACCRETION
- 100-600 KM SIZED ASTEROID ACCRETION/MELTING/CORE FORMATION
- ASTEROID FRACTIONAL CRYSTALLIZATION/META’ISM

AGE DATA AVAILABLE
PETROLOGICAL / GEOCHEMICAL INTERPRETATION
LOGIC / MODELING

M.Y. 0 5 10 15 20 25 30 35

4566 ± 2 M.Y. (CAI Pb)

ISOTOPES $^{26}$Al $^{107}$Pd $^{182}$Hf

HALF-LIFE 0.7 6.5 9.0 M.Y.

2. Busso., et al, 1999
3. Vanhala & Boss, 2000
10. Taylor, 2001
11. McSween, 1999
INNER SYSTEM ACCRETION  
(LARGELY COMPLETE AT 30 M.Y.)

- DUST AGGREGATION
- METER SIZE PARTICLE AGGREGATION
- KILOMETER SIZE BODY AGGREGATION
- RUNAWAY GROWTH OF PLANETS
  - FRAGMENTATION NOT IN MODELS
- GIANT IMPACTS AND MAGMA OCEANS
  - ADDITIONAL LOSS OF VOLATILE ELEMENTS
  - SEPARATION OF CORE-FORMING LIQUID
- DELAYED CORE FORMATIONS?

$^{182}$Hf / W AGES FOR CORE MAT’L SEPARATION (T0 PLUS 30 M.Y.)
BEGINNING: INNER SOLAR SYSTEM

STATUS OF CURRENT UNDERSTANDING

M.Y. 0                10               20               30    40              50              60                70 80                     M.Y.

4566 ± 2 M.Y. (CAI Pb)

ISOTOPES  

\( ^{26}Al \)  \( ^{107}Pd \)  \( ^{182}Hf \)

HALF-LIFE 0.7    6.5    9.0 M.Y.

10. Taylor, 2001
11. McSween, 1999
POTENTIAL TERM PAPER TOPICS

• 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