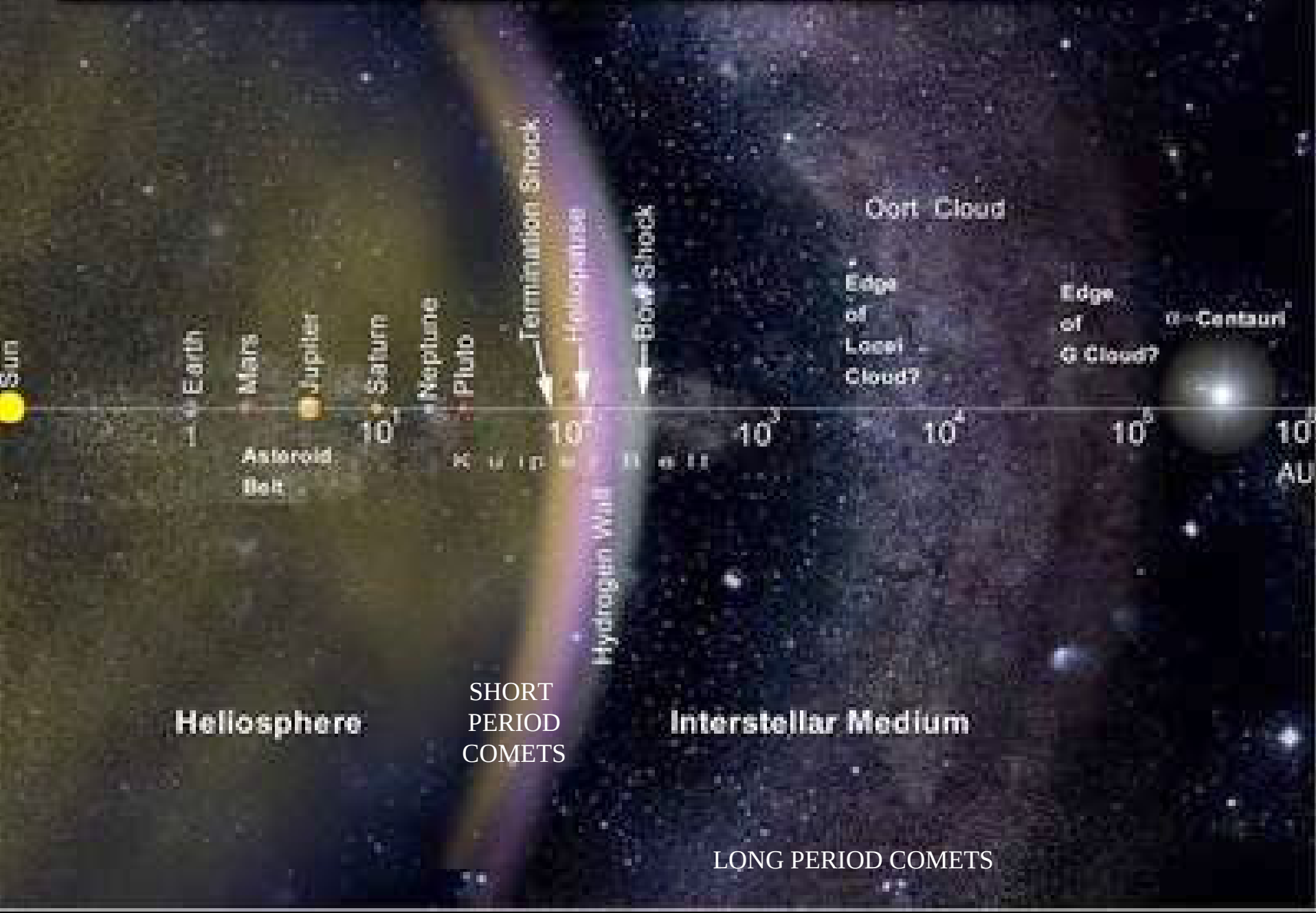
BEGINNING OF THE SOLAR SYSTEM

A MODEL IN-WORK

NEEP 533: Lecture 7

Harrison H. Schmitt



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**

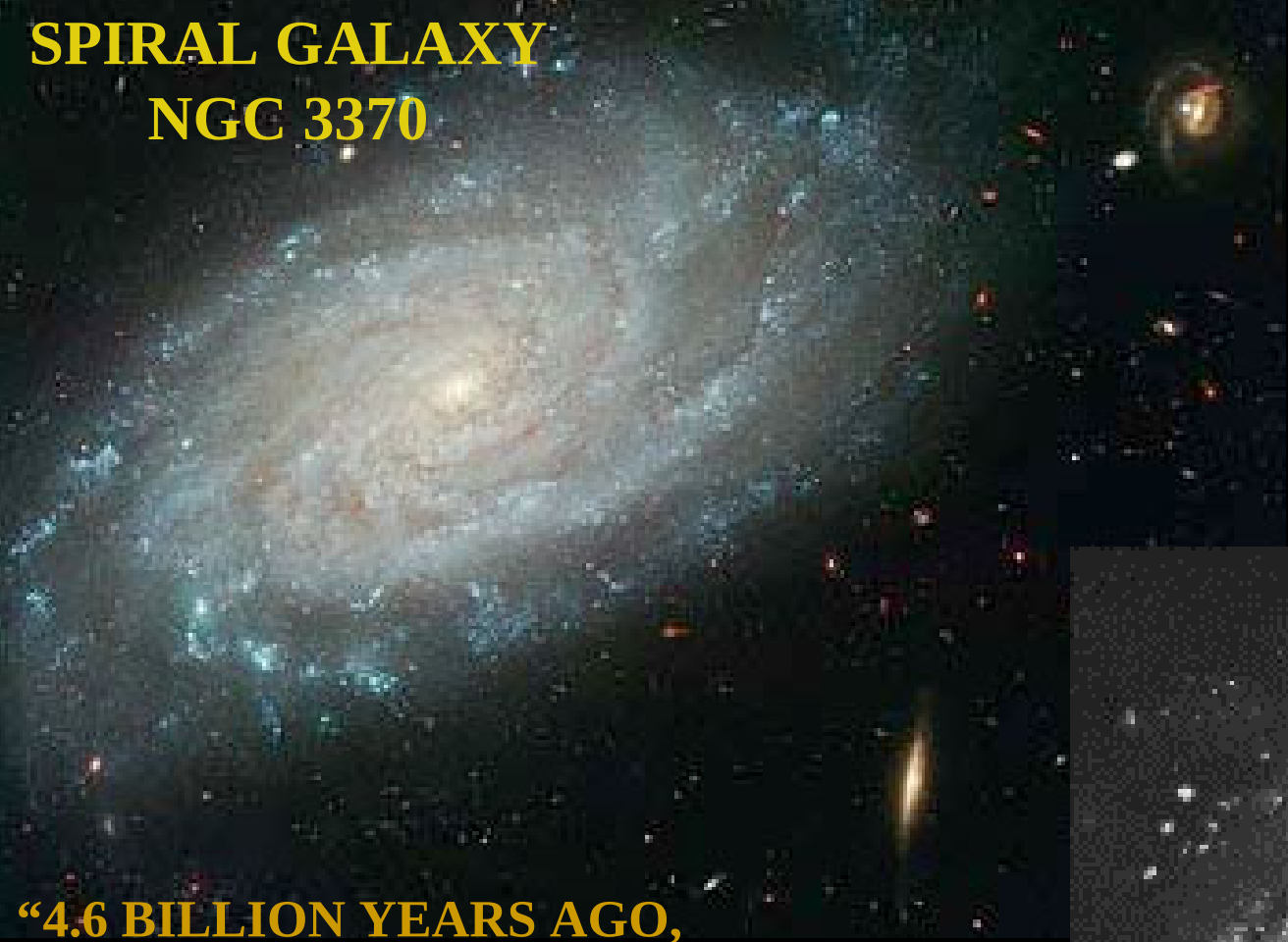
ASTRONOMICAL OBSERVATIONS

- **MOLECULAR CLOUDS**
  - **UV RADIATION SIMPLIFIES ORGAINICS**
- **AGB STARS (ASYMPTOTIC GIANT BRANCH)**
  - **s-process synthesis**
- **TYPE II SUPERNOVAS**
  - **r-process synthesis**
- **MAIN SEQUENCE STAR FORMATION**
  - **SUN-LIKE, SINGLE STARS EXIST**
  - **T-TAURI EVENTS EXIST**
  - **FU-ORIONIS EVENTS EXIST**

COSMO-ISOTOPIC CLOCKS

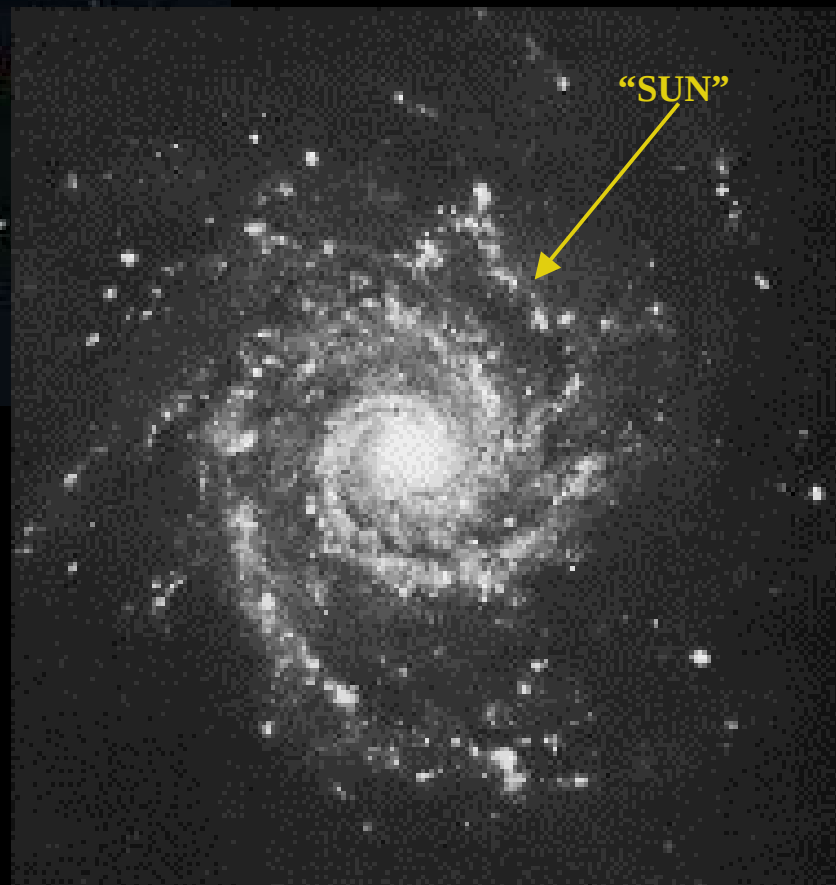
PARENT/DAUGHTER	HALF-LIFE (10^6 YR.)
ALUMINUM-26 / MAGNESIUM-26	0.73
POTASSIUM-40 / ARGON-40 & CALCIUM-40	1270
CALCIUM-41 / POTASSIUM-41	1
MANGANESE-53 / CHROMIUM-53	3.7
IRON-60 / NICKEL-60	1.5
RUBIDIUM-87 / STRONTIUM-87	48.800
LEAD-107 / SILVER-107	5.5
IODINE-129 / XENON-129	15.7
SUMARIUM-146 / NIODENIUM-142	103
SUMARIUM-147 / NIODENIUM-143	106,000
LUTICIUM-176 / HAFNIUM-176	35,700
HAFNIUM-182 / TUNGSTEN-182	9
REHNEIUM-187 / OSMIUM-187	41,600
PLATINUM-190 / OSMIUM-186	450,000
THORIUM-232 / LEAD-208	14,010
URANIUM-235 / LEAD-207 *LEAD-LEAD AGE*	704
URANIUM-238 / LEAD-206	4469
PLUTONIUM-244 / FISSION XE	80

RED CURRENTLY MOST USEFUL



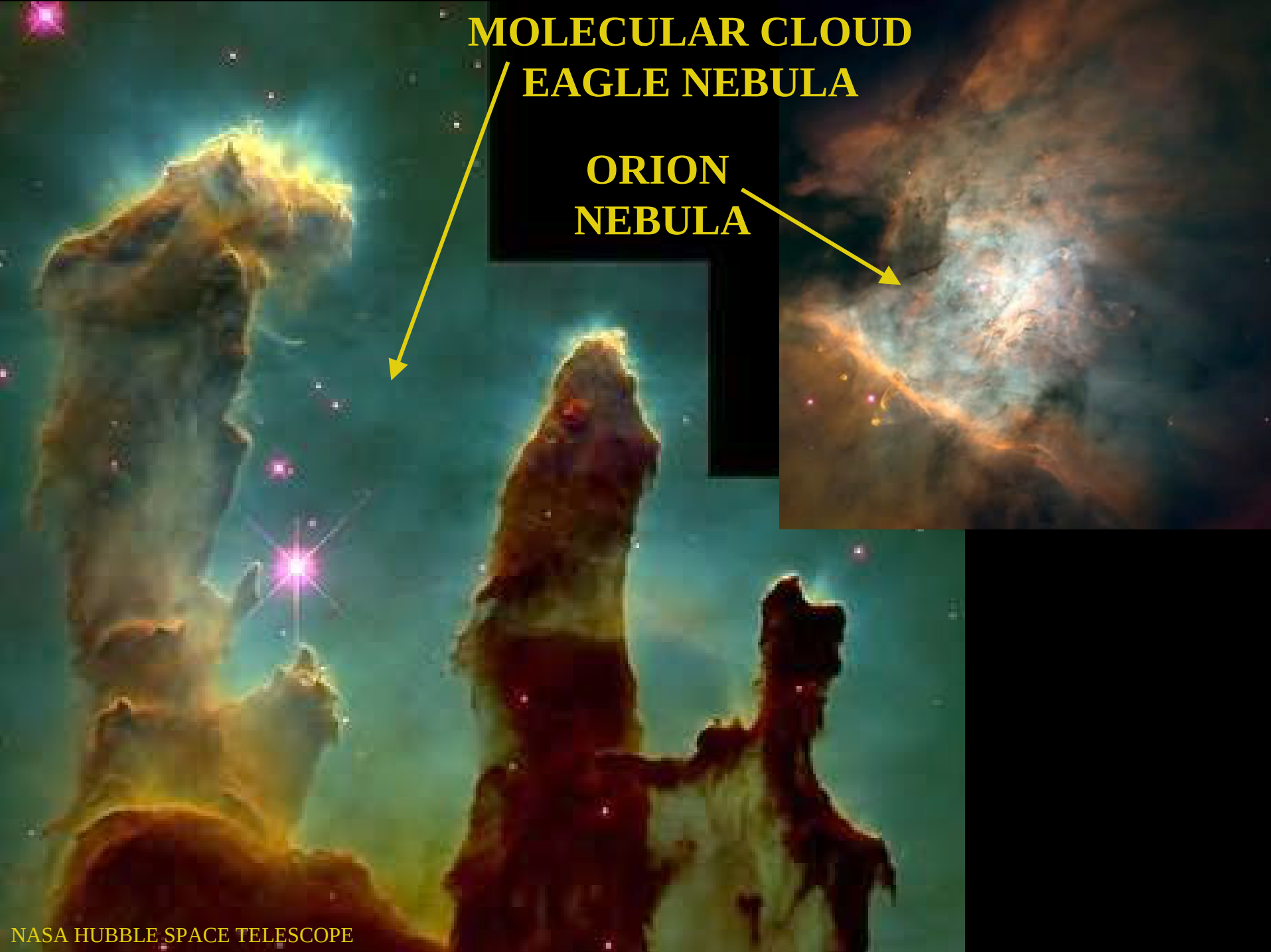
SPIRAL GALAXY
NGC 3370

SPIRAL GALAXY
M74 (NGC 628)



"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
NASA HUBBLE SPACE TELESCOPE

PRE-NEBULA MOLECULAR CLOUD - 1

- **MODEL OF HABITABLE ZONE OF THE MILKY WAY GALAXY (GONZALES, ET AL, 2001; LINEWEAVER, ET AL, 2004)**
  - **7-9 PARSECS FROM GALATIC 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 H_2/cm^3**
- **SILICATE DUST**
  - **OLIVINE AND PYROXENE (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 CONTRIUTORS**

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**
  - **=< 2 SOLAR MASSES**
  - **ADEQUATE DENSITY**
  - **LOW ANGULAR MOMENTUM (ROTATION RATE)**
  - **ISOLATION FROM OTHER STAR FORMATION**

CAI = CALCIUM-ALUMINUM INCLUSIONS IN METEORITES: HIGH TEMPERATURE CRYSTALLIZATION, REFRACTORY MINERALS
"FUN" = FRACTIONATION AND UNKNOWN NUCLEAR

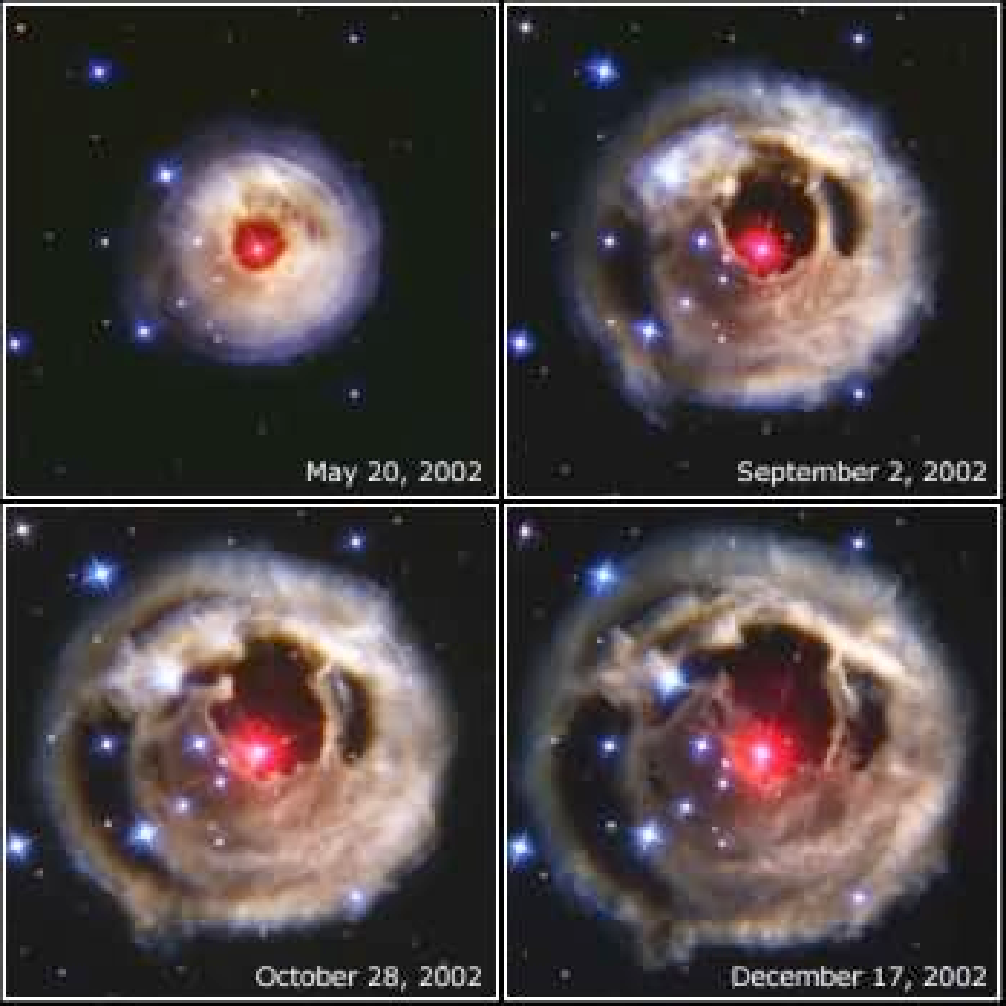
PRE-NEBULA MOLECULAR CLOUD - 5

- **TRIGGER FORGRAVITATIONAL COLLAPSE OF SUB-CLOUD (T_0 MINUS ~0.15 M.Y.)**
  - **GRAVITAIONAL 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**

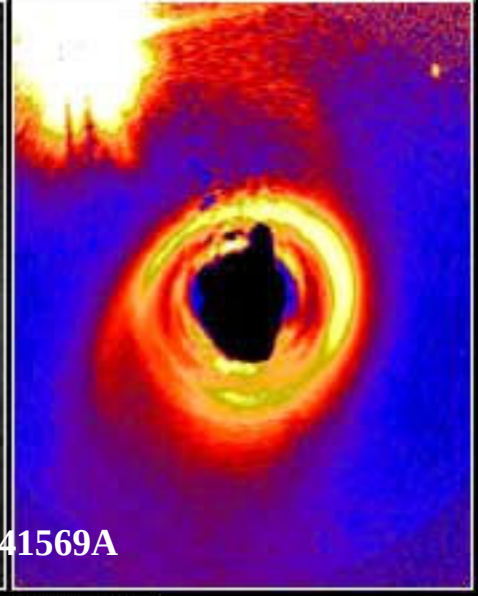
- **IN-FALL FROM PARENT CLOUD**
  - **NEBULAR SHOCK FRONTS ABOVE AND BELOW ECLIPTIC**

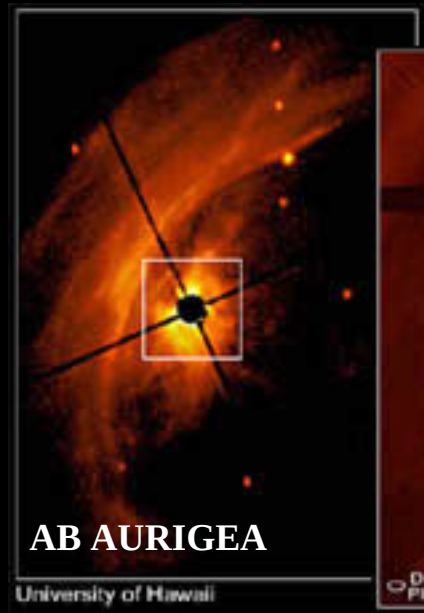
MILKY WAY SUPERNOVA



1987A SUPERNOVA

HD 141569A



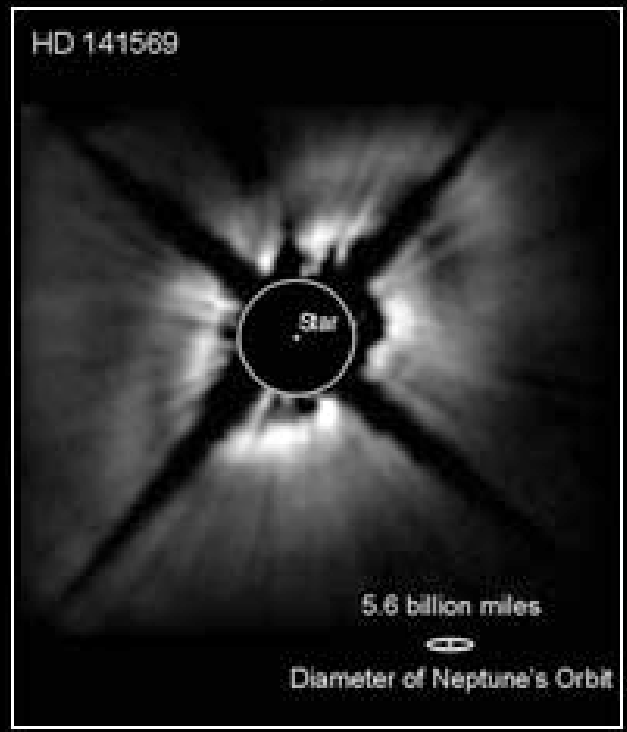


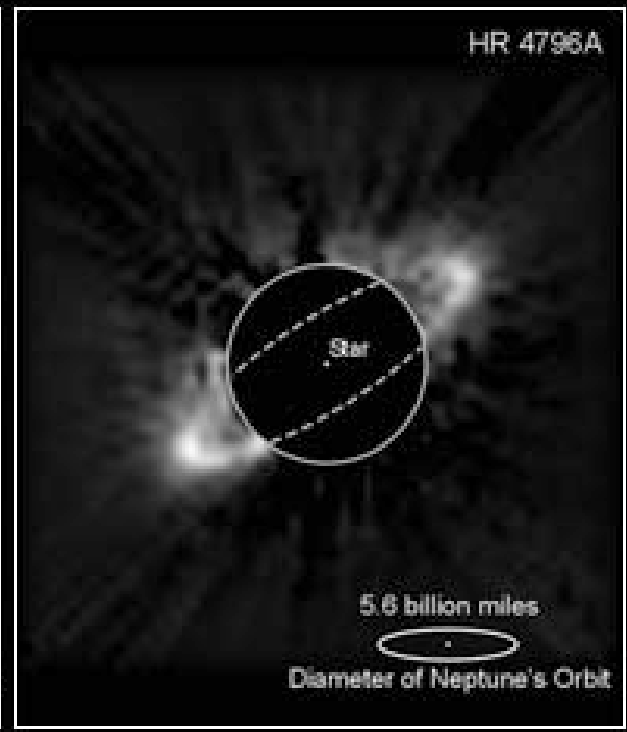
AB AURIGEA

University of Hawaii

Edge-On Disk · Beta Pic HST · WFPC2

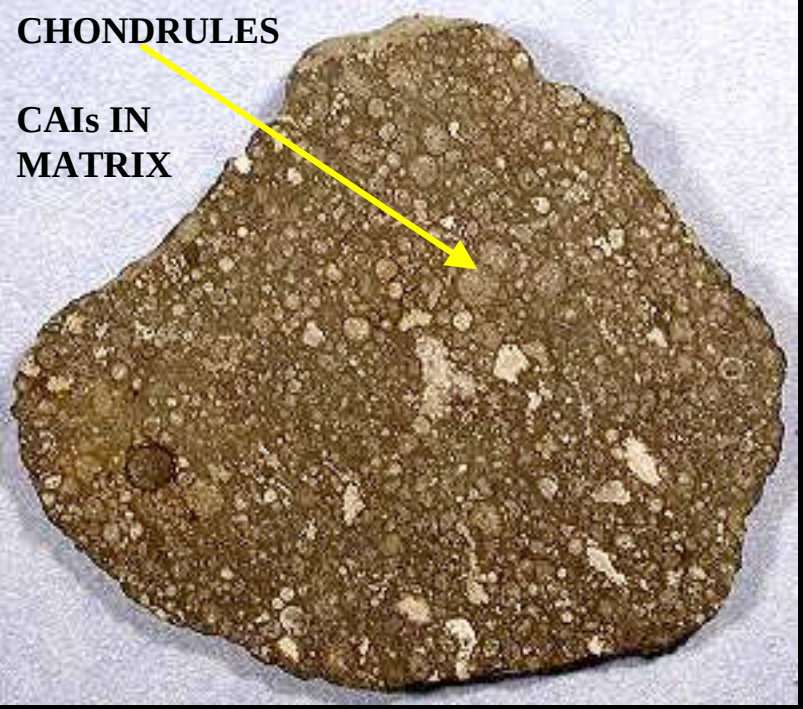
PRC95-38 · ST ScI OPO · October 9, 1995 · A. Schultz (CSC), NASA





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**



ALLENDE, CV3

ORGUEIL, CI-1

MEANWHILE, WHAT ARE CARBONACEOUS CHONDRITES?

MURCHISON, CM2

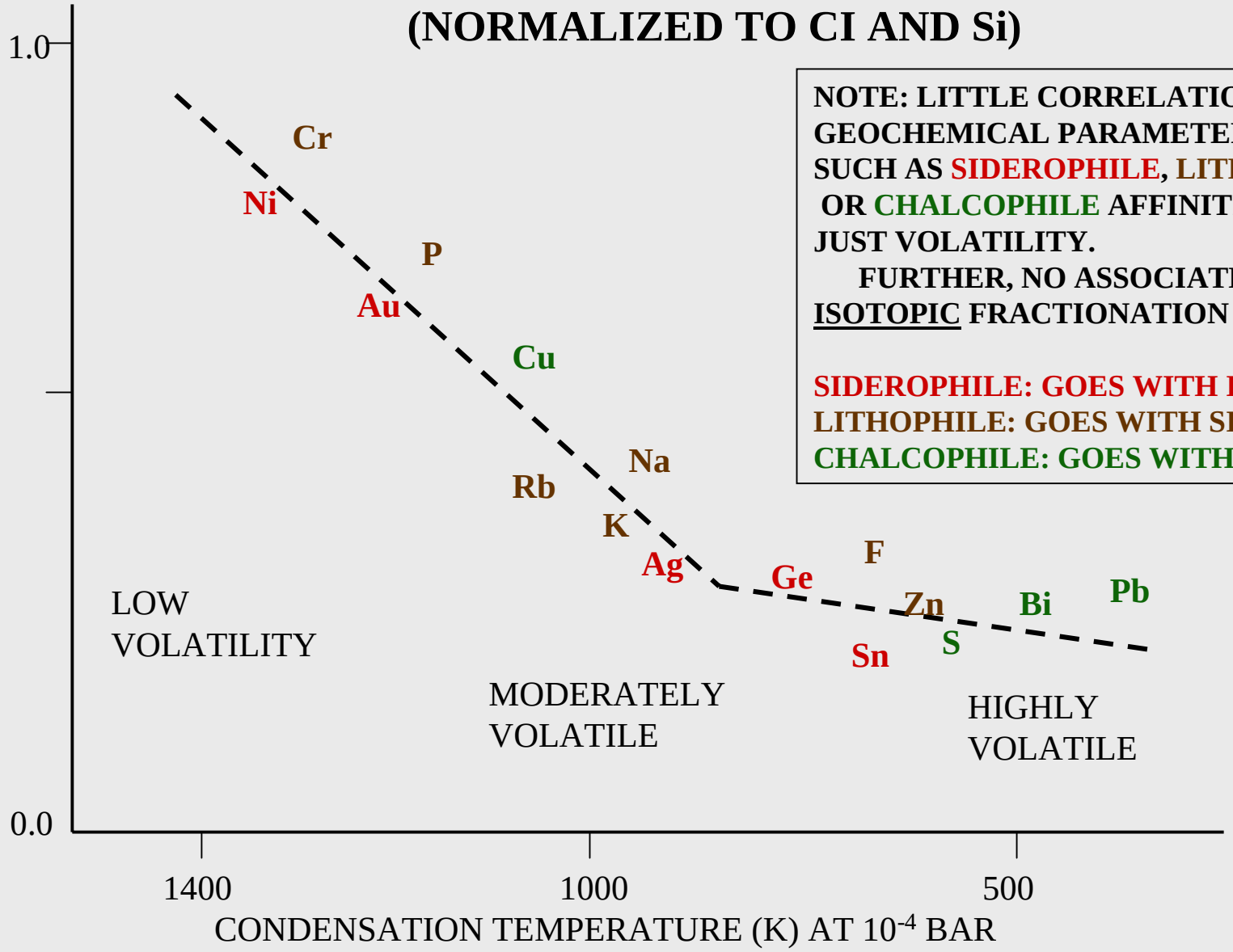
EARLY NEBULAR EVOLUTION - 2

- **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)

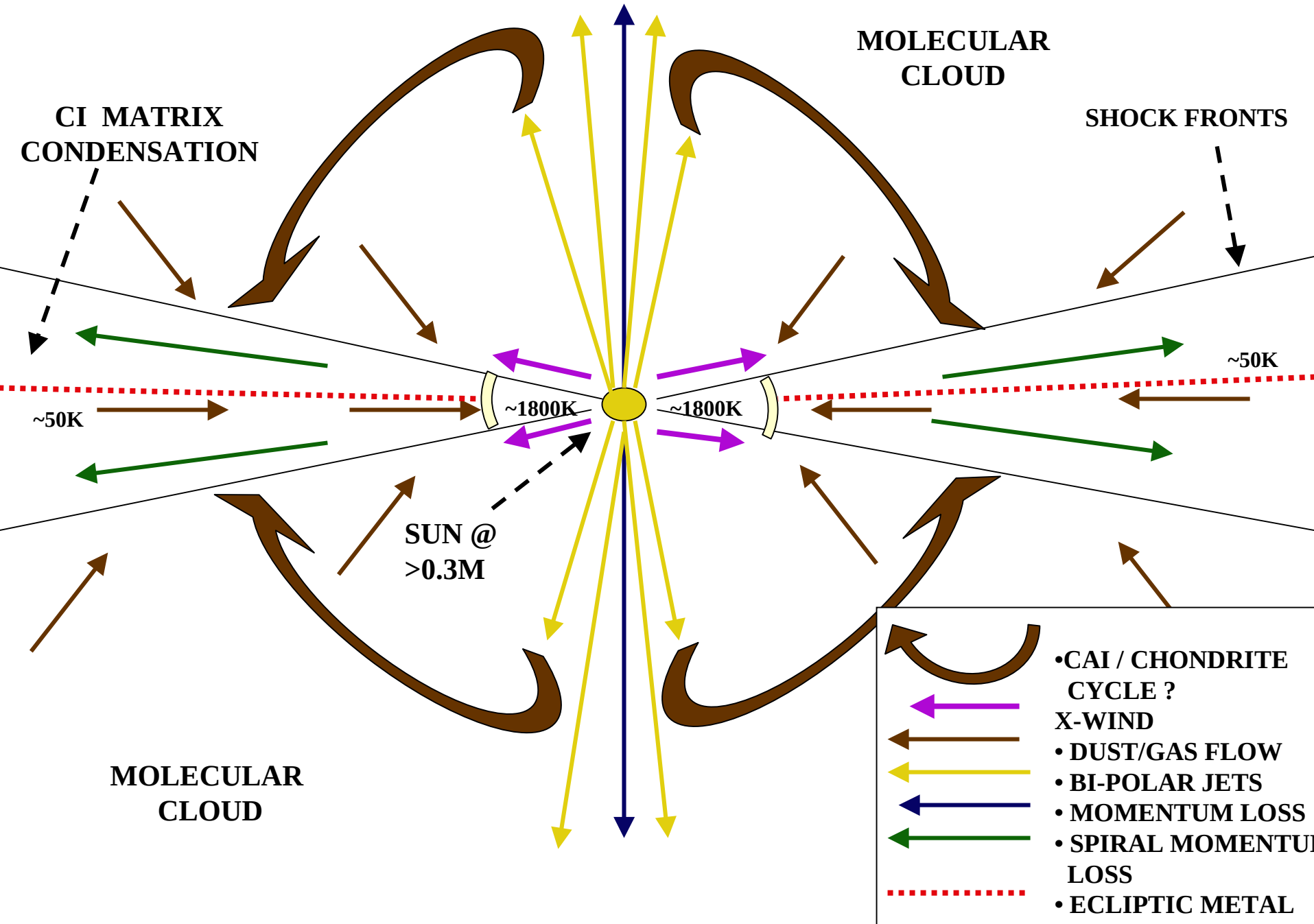


NOTE: LITTLE CORRELATION WITH GEOCHEMICAL PARAMETERS, SUCH AS SIDEROPHILE, LITHOPHILE, OR CHALCOPHILE AFFINITIES JUST VOLATILITY.

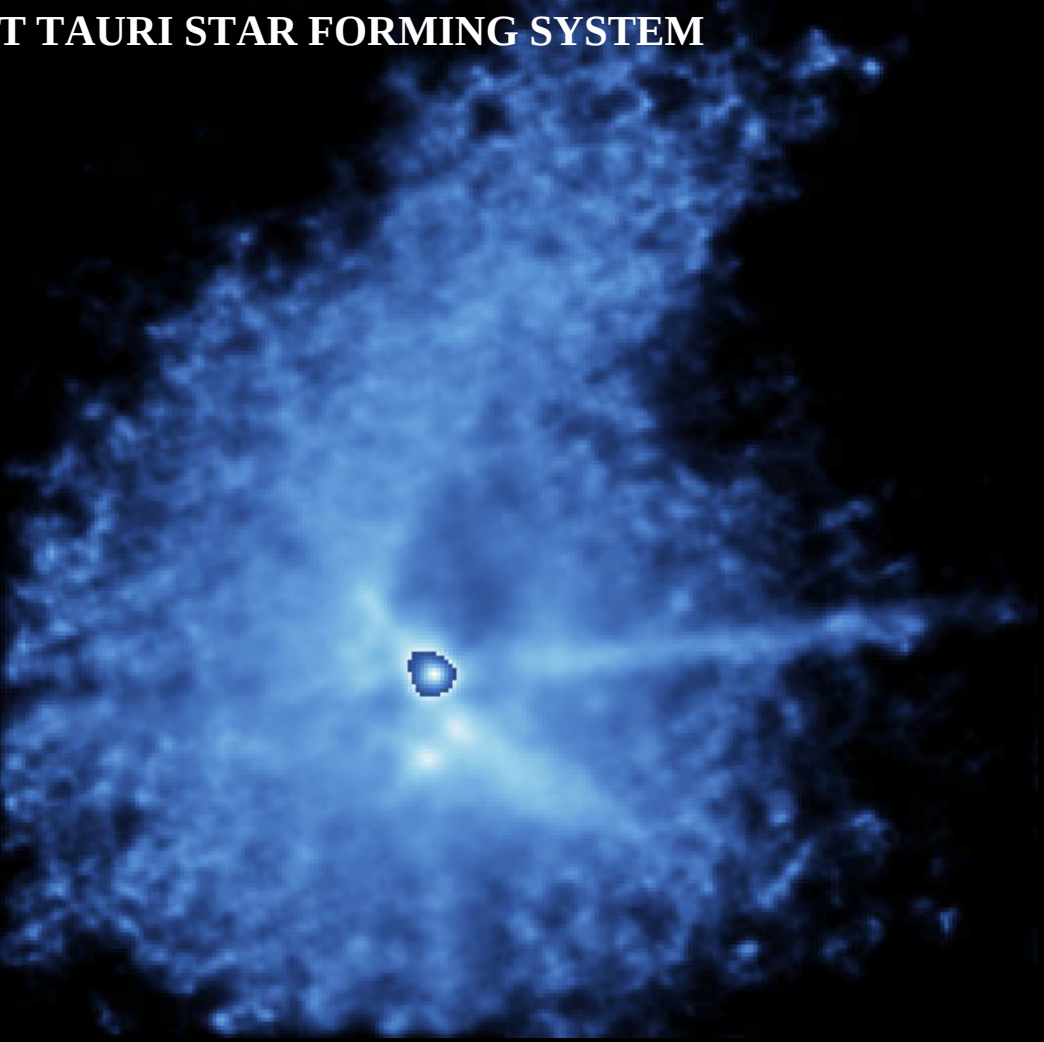
FURTHER, NO ASSOCIATED ISOTOPIC FRACTIONATION

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

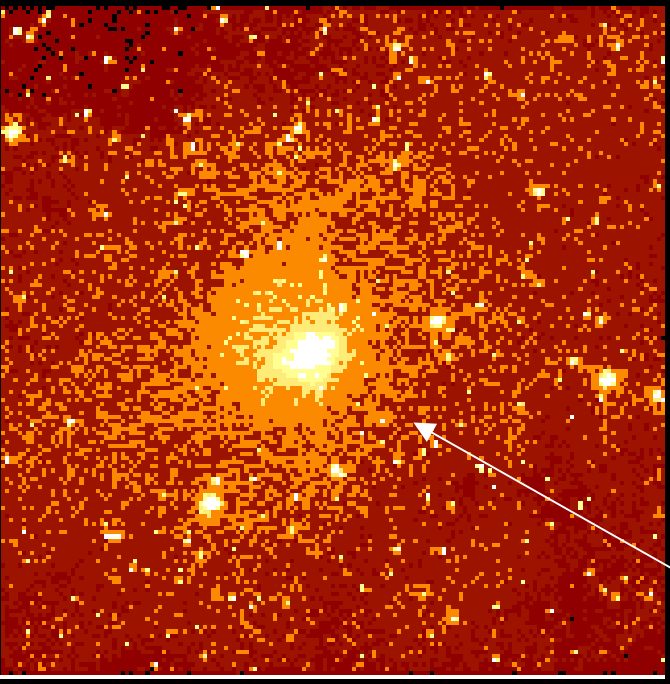
NEBULAR DYNAMICS AT T_0 ±50,000 YEARS

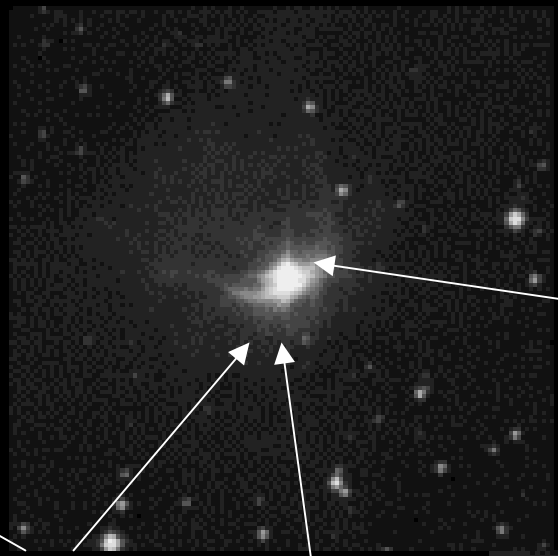


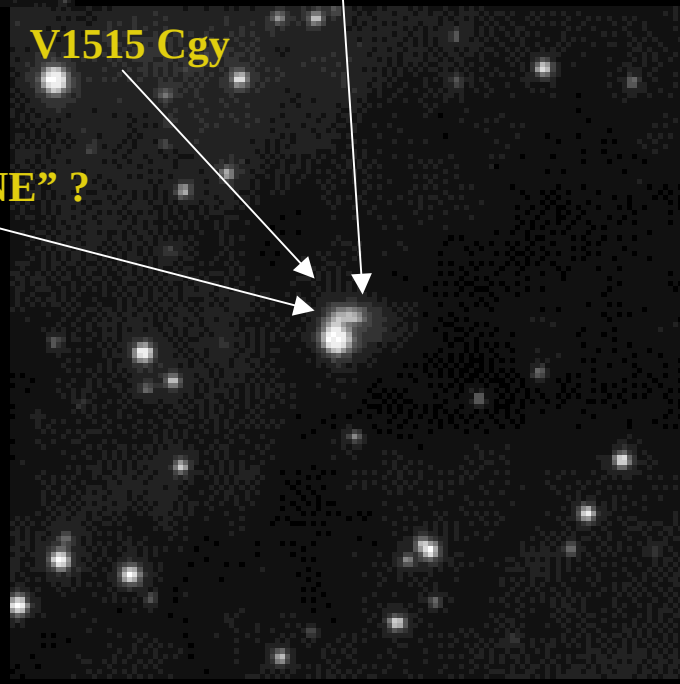
T TAURI STAR FORMING SYSTEM



FU ORIONIS GAS CLEARLING EVENTS







GAS ?

FU ORIONIS

V1515 Cgy

"SNOW LINE" ?

CAUSE OF DEVOLATILIZATION WITHOUT ISOTOPIC FRACTIONATION

- **SOLAR ACTIVITY CLEARED ELEMENTS WHOSE CONDENSATION TEMPERATURES ARE LESS THE 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 ± 2 M.Y. ago)**
  - **LEAD-LEAD AGE**
  - **FINE GRAINED CAIs ARE VERY HIGH TEMPERTURE 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**
    - **$^{16}0$ MUCH HIGHER THAN OTHER METEORITES**

EARLY NEBULAR EVOLUTION - 3B

- **ACCRETION OF CENTIMETER SIZED DUST BALLS**
  - **TURBULENT / GASEOUS ENVIRONMENT (10^{-4} - 10^{-6} T0RR)**
  - **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 (~ 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

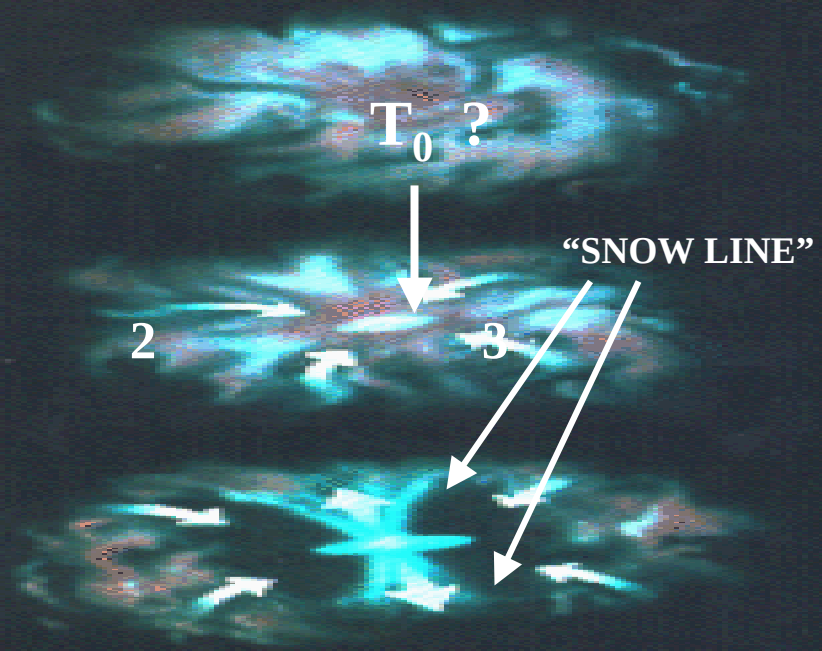
OUTER AND MID NEBULA

- **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 MAT'L CONDENSED



5 • SUN ENTERS MAIN SEQUENCE
• EARLY MID-NEBULA ACCRETION

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

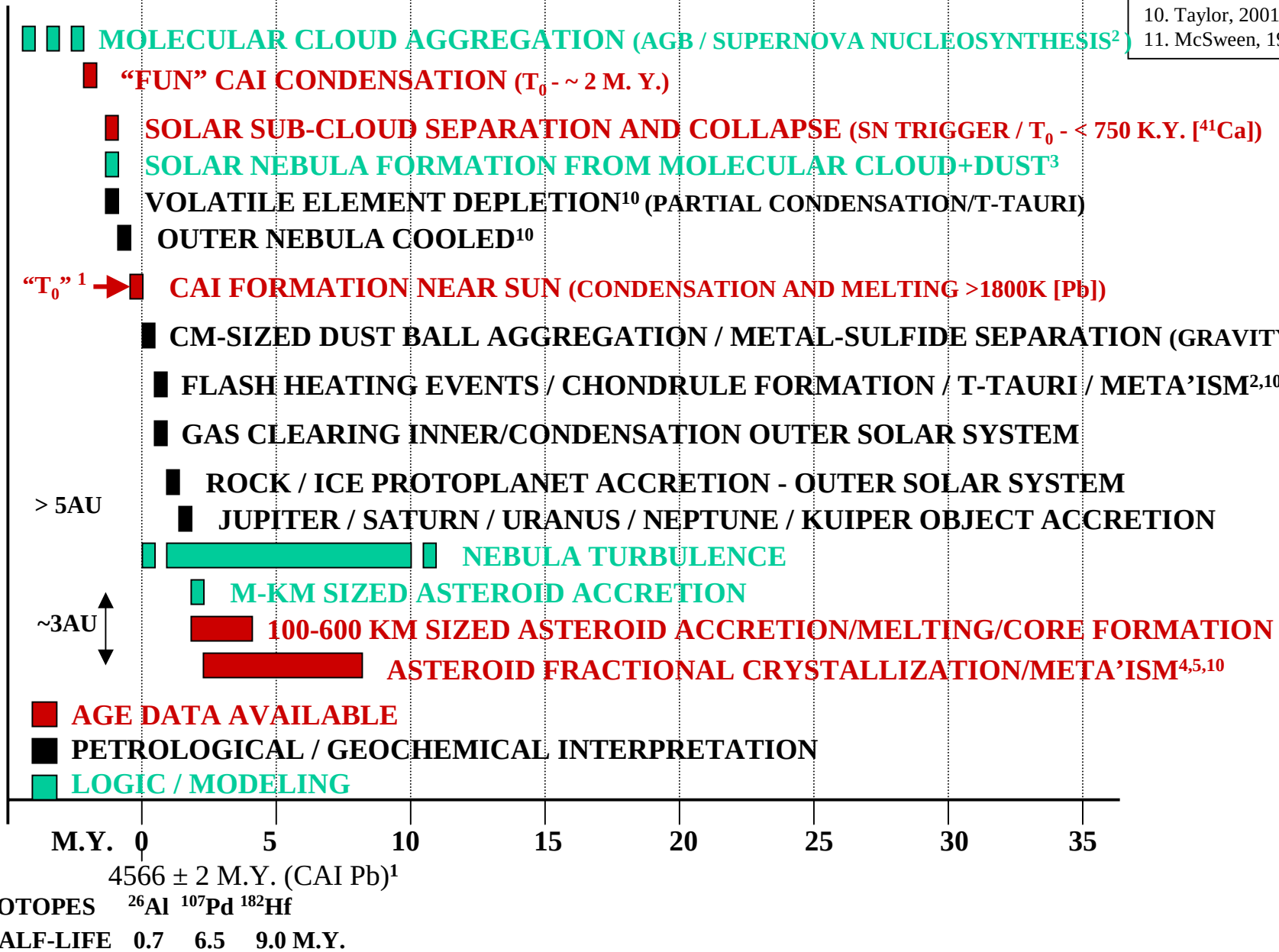
EARLY MID-NEBULAR EVENTS

- **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



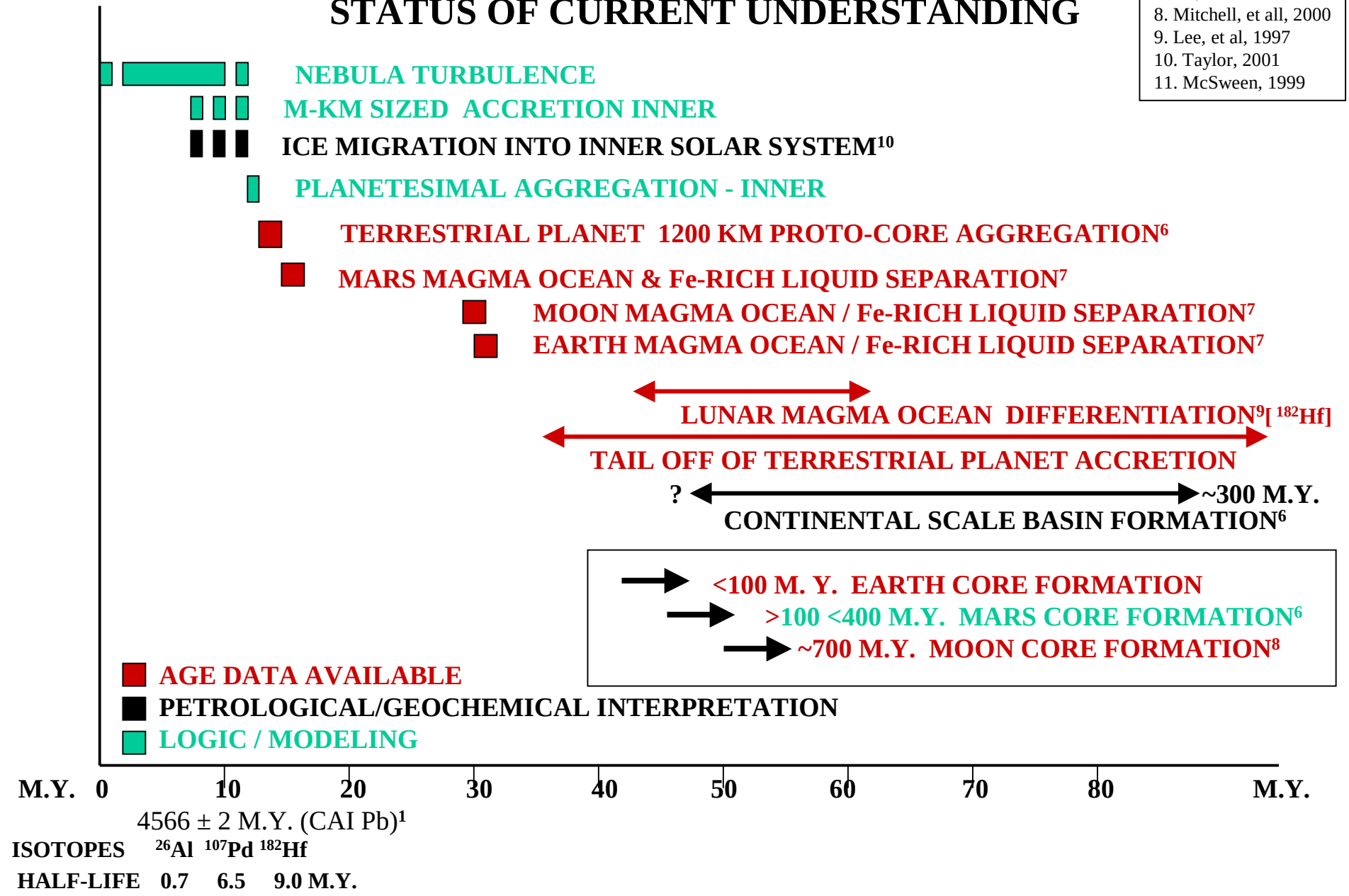
1. Allègre, et al, 1995
2. Busso,, et al, 1999
3. Vanhala & Boss, 2000
4. Carlson & Lugmire, 2000
10. Taylor, 2001
11. McSween, 1999

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



4566 ± 2 M.Y. (CAI Pb)[1]

ISOTOPES	^{26}Al	^{107}Pd	^{182}Hf
HALF-LIFE	0.7	6.5	9.0 M.Y.

5. Lee, et all,
6. Schmitt, 2003
7. Yin, et al, 2001 and Kline, et al 2001
8. Mitchell, et all, 2000
9. Lee, et al, 1997
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**