APPENDICES (Supplementary Material)

A. Brown Dwarfs

B. Planets

C. The CNO Tri-Cycle

D. The Structure of the Sun and the Solar Neutrino Problem

E. Star Formation

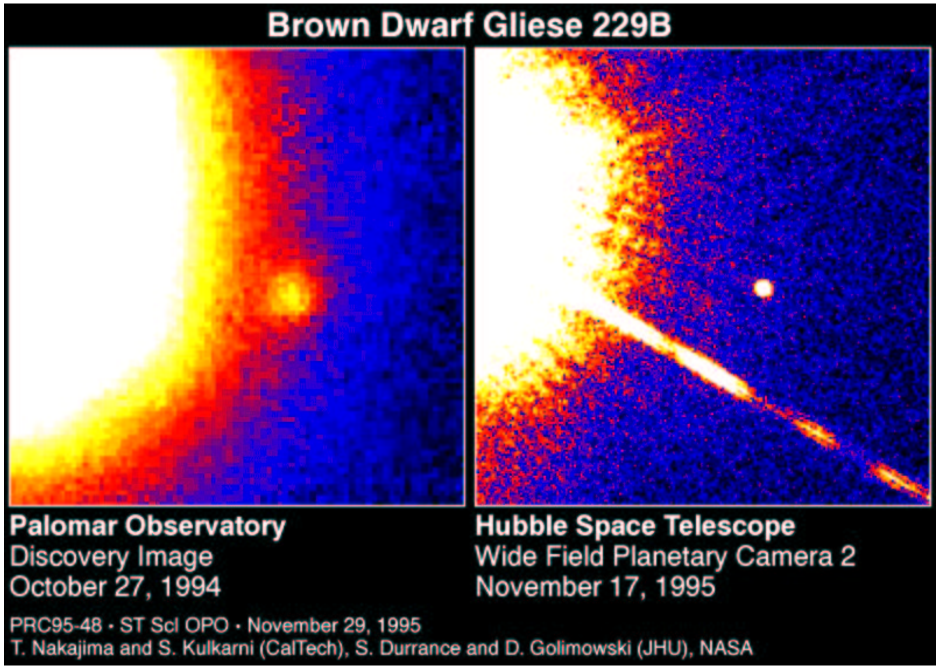
F. The Rings around SN 1987A

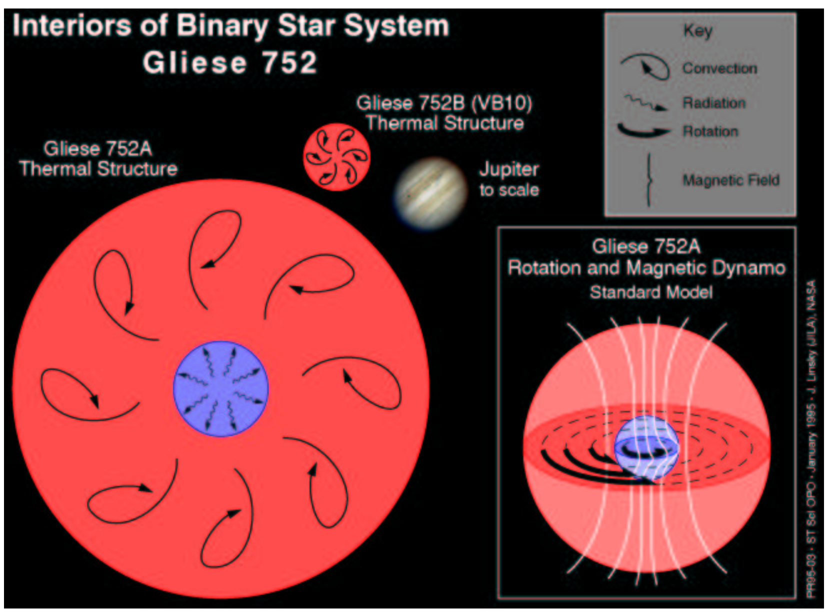
G. Gamma-Ray Bursts

H. Elliptical Orbits

A. Brown Dwarfs (Supplementary)

- star-like bodies with *masses too low* to create the central temperature required *to ignite fusion reactions* (i.e. $M \lesssim 0.08\,M_\odot$ from theory).
- reach maximum temperature by gravitational contraction and then cool steadily becoming undetectable, with surface temperature less than 1000 K, after a few billion years (stars with $T_{\rm eff} < 2000$ and $L \lesssim 5 \times 10^{-4}\,L_\odot$ mainly emit in the infrared).
- Brown dwarfs are prime dark matter candidates (only detectable in the solar neighborhood)
- *Recent developments* leading to *successful searches:*
  - (i) Larger optical and IR detectors (CCDs) with large telescopes (8-10 m) (e.g. nearby, young clusters)
  - (ii) All-sky IR surveys.
  - (iii) Development of powerful IR spectrographs.
- *Spectral signatures* of Brown Dwarfs:
  - (i) *Strong Li lines* - Brown Dwarfs retain original Li for ever.
  - (ii) *Methane bands* c.f. Jupiter - dominant when $T_{\rm eff} < 1500$ K.
  - (iii) *L stars* - bands of FeH, CrH appear instead of TiO, VO *(M stars);* also prominent lines of Cs I, Rb I - related to dust formation at $T_{\rm eff} < 2000$ K.
- *Missing Mass:* Detections so far indicate that Brown Dwarfs are *not sufficiently abundant* to account significantly *for the missing mass.*

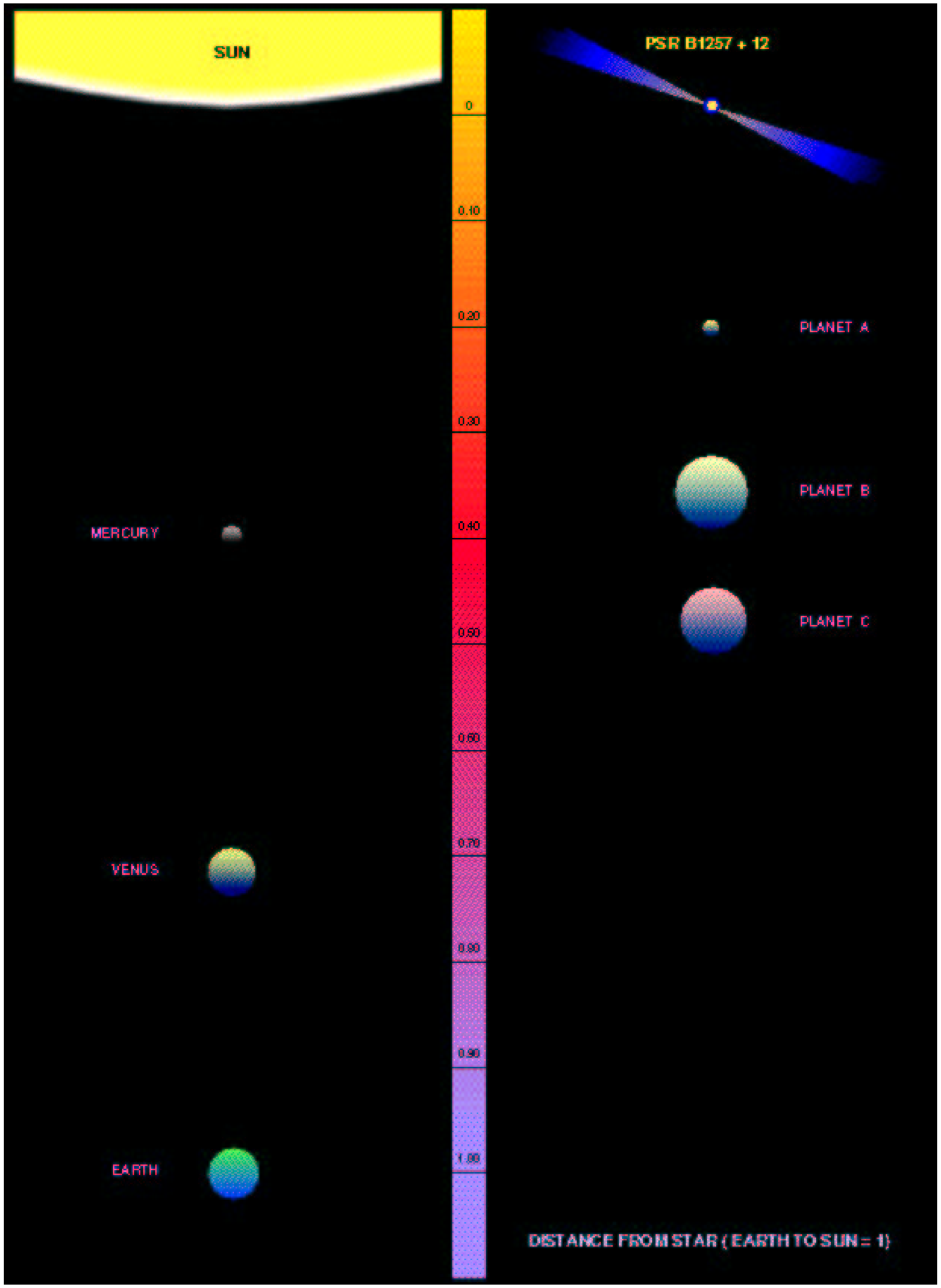




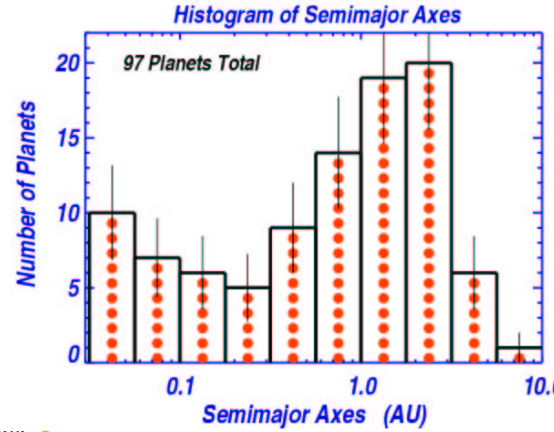
B. Extrasolar Planets (Supplementary)

(http://ast.star.rl.ac.uk/darwin/links.html#exoplanets)

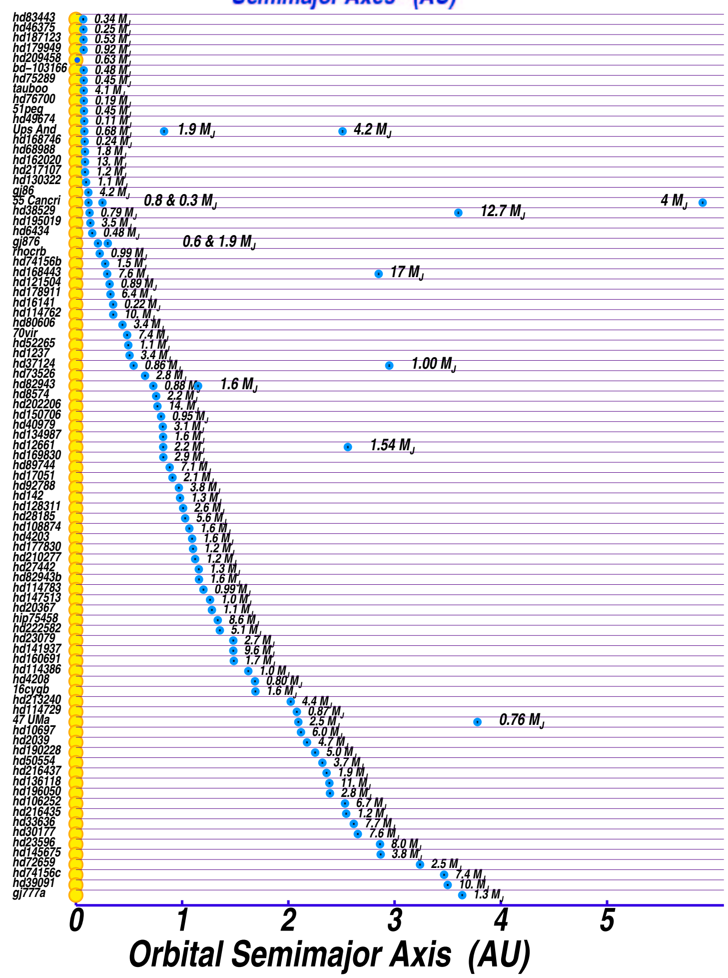
- large numbers of planets have been discovered in the last decade
- first planetary system detected outside the solar system was around a *millisecond pulsar, PSR 1257+12*, a rapidly rotating neutron star, spinning with a period of 6.2 msec (Wolszczan 1992)
  - ▷ 3 planets with masses $> 0.015\,M_\oplus$, (25 d), $> 3.4\,M_\oplus$ (66 d), $> 2.8\,M_\oplus$ (98 d)
  - ▷ detection possible because of extreme timing precision of pulsar (measure effects of tiny reflex motion of pulsar caused by planets)
  - ▷ planets almost certainly formed *after the supernova* that formed the neutron star, out of material that was left over from *disrupted companion star* (?) and formed a disk (similar to planet formation in the solar system?)
- *since 1995* many planets (generally very massive $>> M_{Jup}$) have been discovered around normal stars



SUN
PSR B1257 + 12
MERCURY
VENUS
EARTH
PLANET A
PLANET B
PLANET C
0
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
DISTANCE FROM STAR (EARTH TO SUN = 1)



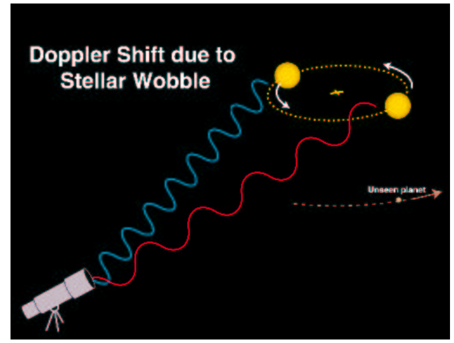
Histogram of Semimajor Axes
97 Planets Total
Number of Planets
0
5
10
15
20
0.1
1.0
10.0
Semimajor Axes (AU)

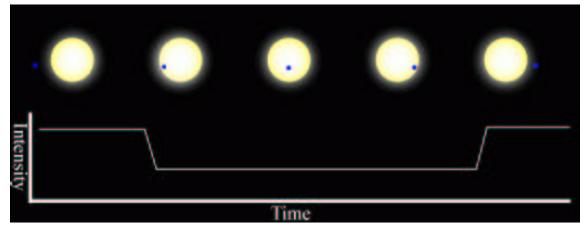


0
1
2
3
4
5
Orbital Semimajor Axis (AU)

Detection Techniques for Extrasolar Planets

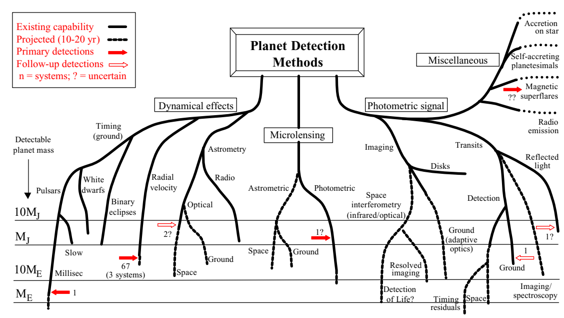
- ***Direct Imaging:*** relies on the fact that planets reflect their parent star's light. So far unsuccessful.
- ***Photometry – Planetary Transits.*** Photometry can be used to detect a change in the brightness of a star, as in the case when a planet transits (passes in from of) its parent star.
- ***Astrometry:*** by detecting the wobbling motion of a star in the sky due to the motion of the planet
- ***Radial velocity:*** Measure the periodic variation of the velocity of the central star (from the Doppler shifts of spectral lines) caused by the orbiting planets
- Present methods favour detection of massive (gaseous) planets (super-Jupiters) close the central star (→ large radial velocity variations); they are probably completely *unrepresentative* of the majority of planetary systems (which are ubiquitous).



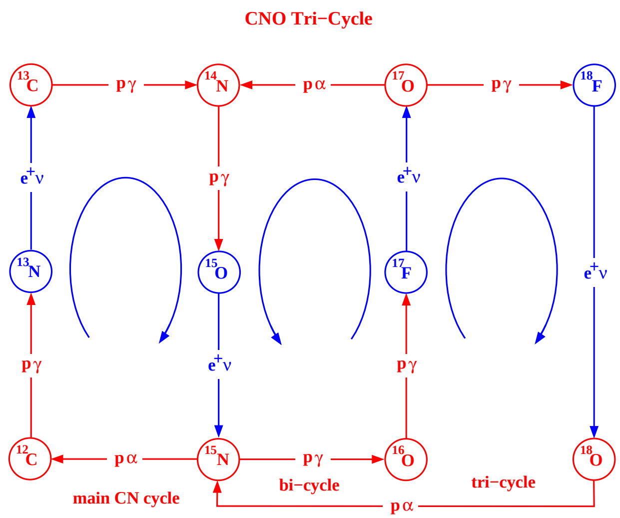


Planet Detection Methods

Michael Perryman, April 2001



C. THE CNO TRI-CYCLE



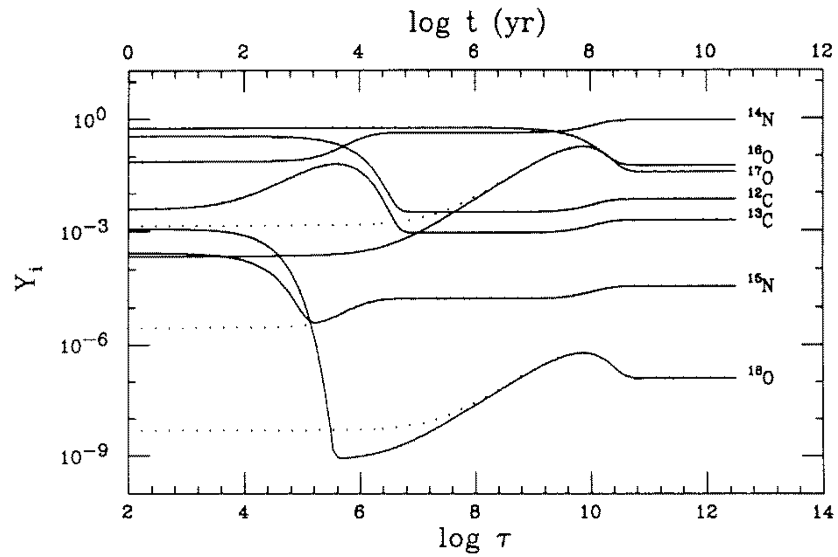


Figure A.4: Same as figure A.3 for $T = 20 \times 10^6$ K.

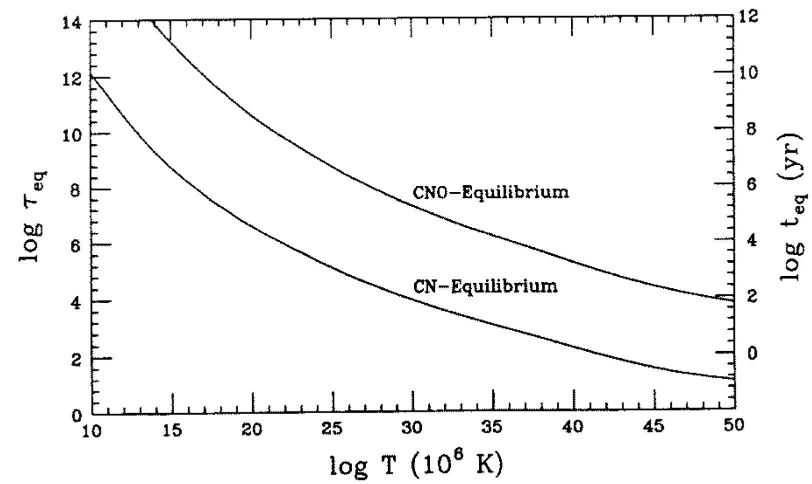


Figure A.8: Equilibration times for the CN main-cycle and the CNO tri-cycle as a function of temperature.

- once every ~ 2500 times the reaction ^{15}N + H produces ^{16}O + γ

→ break-out from the main CN cycle

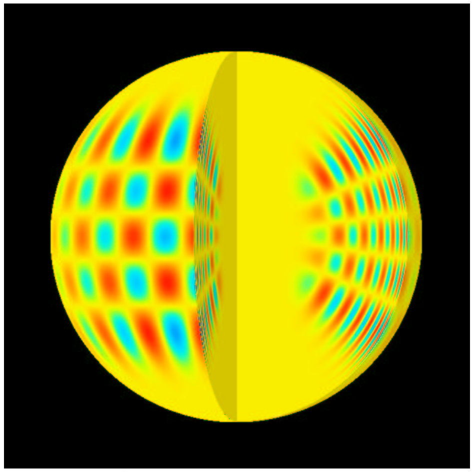
→ *bi-cycle* and of equal importance *tri-cycle* (^{17}O + H produces ^{14}N + α and ^{18}F + γ in comparable numbers)

- ^{16}O (another seed element) is added to the main CN cycle
- *equilibration timescale for CN cycle:* $\sim 10^6$ yr ($T \sim 15 \times 10^6$ K)
- *equilibration timescale for all cycles:* $\sim 10^{11}$ yr ($T \sim 15 \times 10^6$ K)

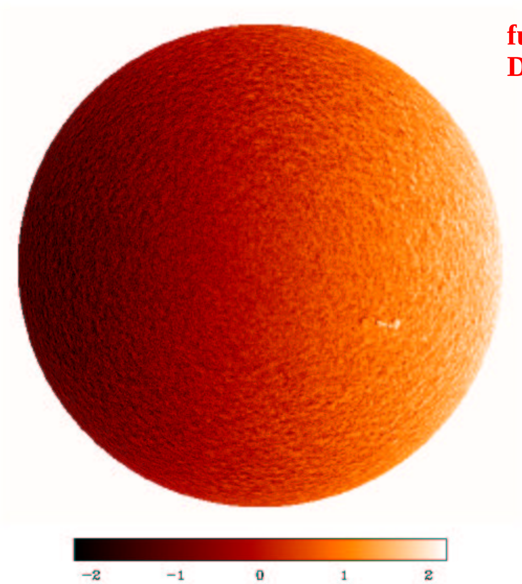
→ CN cycle is usually in equilibrium, CNO cycle may not be

HELIOSEISMOLOGY (I)

acoustic mode
in the Sun
(p mode
n=14, l -20)



full-disk
Dopplergram



velocity (km/s)

D. STRUCTURE OF THE SUN (ZG: 10, CO: 11)

- The *Sun* is the only star for which we can *measure* internal properties → test of stellar structure theory
- *Composition* (heavy elements) from *meteorites*
- *Density, internal rotation* from *helioseismology*
- *Central conditions* from *neutrinos*

HELIOSEISMOLOGY

- The Sun acts as a *resonant cavity, oscillating* in millions of (acoustic, gravity) modes (like a bell)

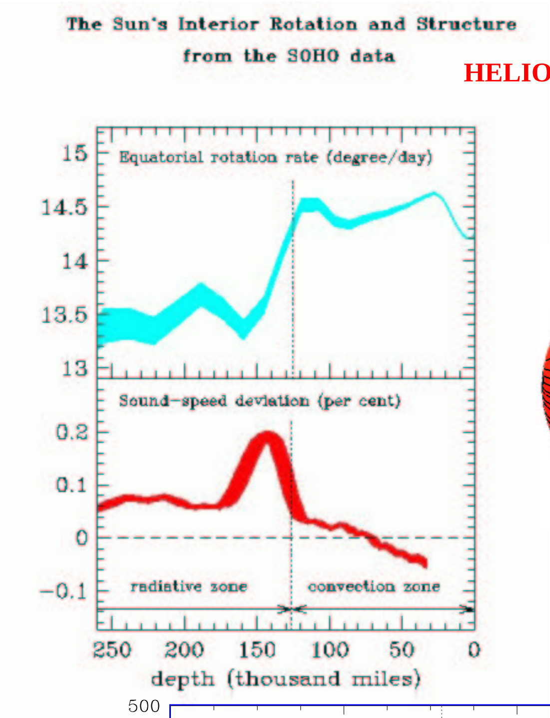
→ can be used to reconstruct the internal density structure (like earthquakes on Earth)

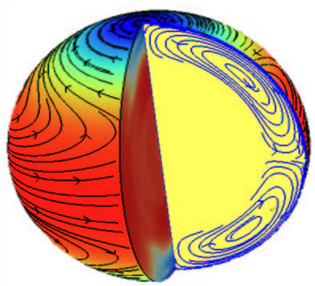
- oscillation modes are *excited* by *convective eddies*
- *periods* of typical modes: *1.5 min to 20 min*
- *velocity amplitudes:* $\sim 0.1\,m/s$
- need to measure *Doppler shifts* in spectral lines relative to their width to an accuracy of 1:10^6
  - ▷ possible with good spectrometers and long integration times (to average out noise)

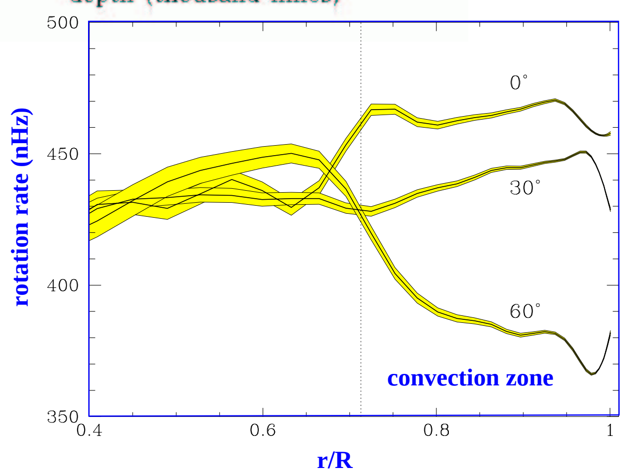
Results

- *density* structure, *sound speed*
- depth of outer *convective zone:* $\sim 0.28\,\mathrm{R}_\odot$
- *rotation* in the core is *slow* (almost like a solid-body) → the core must have been spun-down with the envelope (efficient core–envelope coupling)

HELIOSEISMOLOGY (II)







SOLAR NEUTRINOS (ZG: 5-11, 16-1D, CO: 11.1)

- *Neutrinos,* generated in solar core, *escape* from the Sun and carry away $2-6\,\%$ of the energy released in H-burning reactions
- they can be observed in *underground experiments* $\rightarrow$ *direct probe of the solar core*
- neutrino-emitting reactions (in the pp chains)

$$
\begin{array}{rcll}
{}^{1}\mathrm{H} + {}^{1}\mathrm{H} & \rightarrow & {}^{2}\mathrm{D} + \mathrm{e}^{+} + \nu & \mathrm{E}_{\nu}^{\max} = 0.42\,\mathrm{Mev} \\
{}^{7}\mathrm{Be} + \mathrm{e}^{-} & \rightarrow & {}^{7}\mathrm{Li} + \nu & \mathrm{E}_{\nu}^{\max} = 0.86\,\mathrm{Mev} \\
{}^{8}\mathrm{B} & \rightarrow & {}^{8}\mathrm{Be} + \mathrm{e}^{+} + \nu & \mathrm{E}_{\nu}^{\max} = 14.0\,\mathrm{Mev}
\end{array}
$$

- The *Davis experiment* (starting around 1970) has shown that the neutrino flux is about a factor of 3 lower than predicted $\rightarrow$ *the solar neutrino problem*

The Homestake experiment (Davis)

- *neutrino detector:* underground tank filled with 600 tons of Chlorine ($C_2\,Cl_4$: dry-cleaning fluid)
- some neutrinos react with Cl

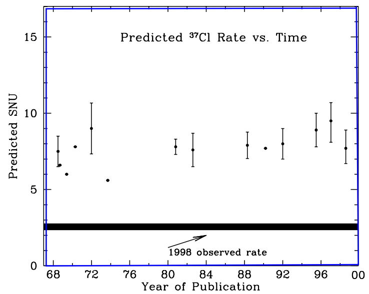
  $\nu_{\mathrm{e}} + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + \mathrm{e}^{-} - 0.81\,\mathrm{Mev}$

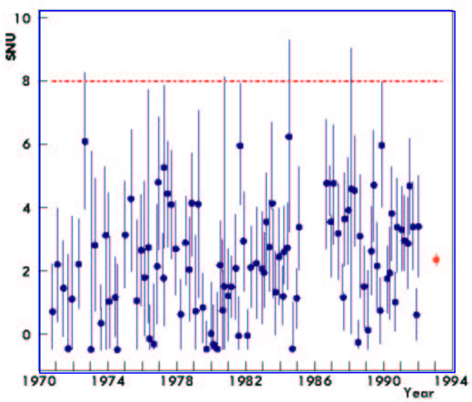
- rate of absorption $\sim 3 \times 10^{-35}\,\mathrm{s}^{-1}$ per ^{37}Cl atom
- every 2 months *each ^{37}Ar atom is filtered out* of the tank (expected number: 54; observed number: 17)
- *caveats*
  - ▷ difficult experiment, only a tiny number of the neutrinos can be detected
  - ▷ the experiment is only sensitive to the most energetic neutrinos in the ^{8}B reaction (only minor reaction in the Sun)

The Davis Neutrino Experiment

Homestake Mine
(with Cl tank)

Model Predictions





Results

Proposed Solutions to the Solar Neutrino Problem

- dozens of solutions have been proposed

1) *Astrophysical solutions*

   ▷ require a *reduction in central temperature* of about 5 % (standard model: 15.6×10^6 K)

   ▷ can be achieved if the solar core is mixed (due to convection, rotational mixing, etc.)

   ▷ if there are *no nuclear reactions in the centre* (inert core: e.g. central black hole, iron core, degenerate core)

   ▷ if there are *additional energy transport* mechanisms (e.g. by WIMPS = weakly interacting particles)

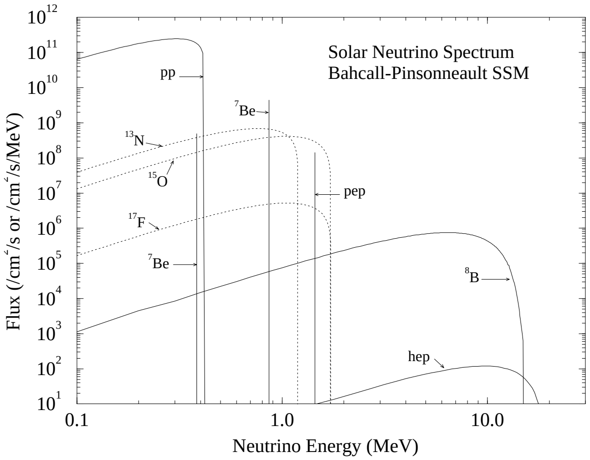
   ▷ most of these astrophysical solutions also change the density structure in the Sun → can now be *ruled out by helioseismology*

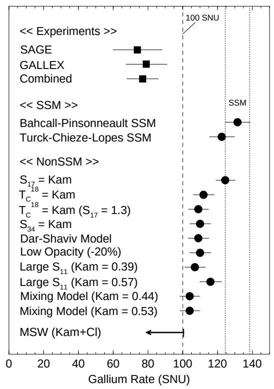
2) *Nuclear physics*

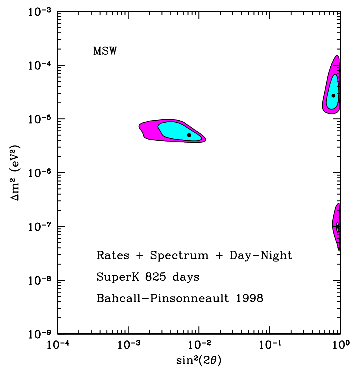
   ▷ errors in *nuclear cross sections* (cross sections sometimes need to be revised by factors up to ~ 100)

   ▷ improved experiments have *confirmed the nuclear cross sections* for the key nuclear reactions

Solar Neutrinos







3) *Particle physics*

- ▷ all neutrinos generated in the Sun are *electron neutrinos*
- ▷ if neutrinos have a *small mass* (actually mass differences), neutrinos may change type on their path between the centre of the Sun and Earth: *neutrino oscillations*, i.e. change from electron neutrino to μ or τ neutrinos, and then cannot be detected by the Davis experiment
- ▷ *vacuum oscillations:* occur in vacuum
- ▷ *matter oscillations (MSW [Mikheyev-Smirnov--Wolfenstein] effect):* occur only in matter (i.e. as neutrinos pass through the Sun)

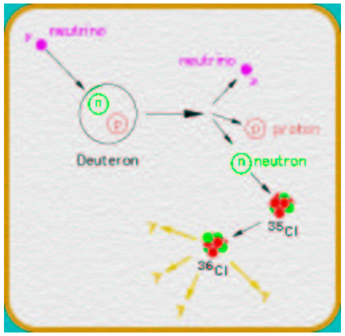
RECENT EXPERIMENTS

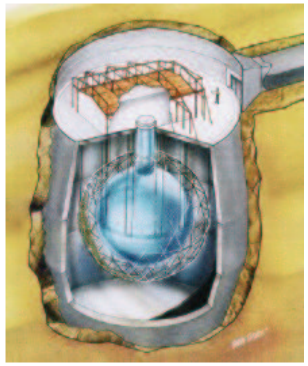
- resolution of the neutrino puzzle requires more sensitive detectors that can also detect neutrinos from the main pp-reaction

1) *The Kamiokande experiment*
(also super-Kamiokande)

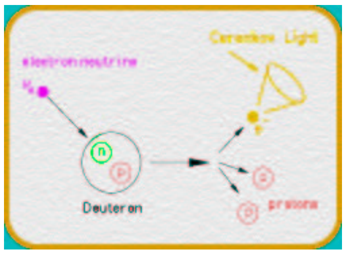
- ▷ uses 3000 tons of ultra-pure water (680 tons active medium) for
$\nu + e^- \to \nu + e^-$ (inelastic scattering)
- ▷ about six times more likely for ν_e than ν_μ and ν_τ
- ▷ *observed flux:* half the predicted flux (energy dependence of neutrino interactions?)

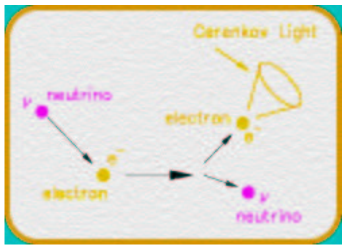
The Sudbury Neutrino Observatory

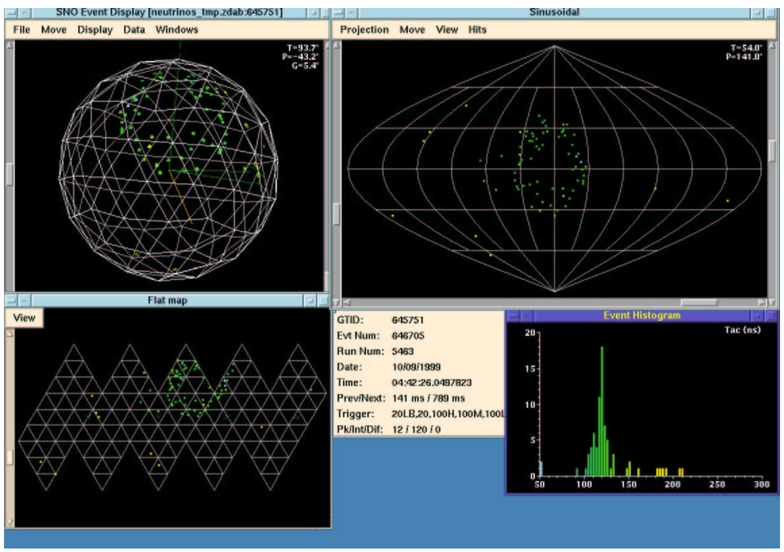




1000 tons of heavy water







2) *The Gallium experiments* (GALLEX, SAGE)

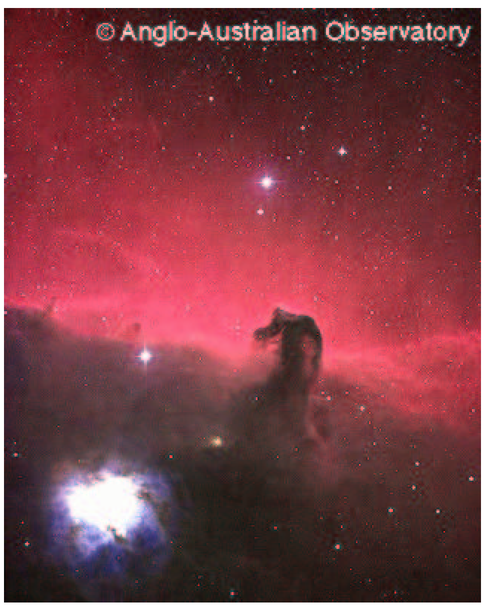
- ▷ uses Gallium to measure low-energy *pp neutrinos* directly
  $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^- - 0.23\,\mathrm{Mev}$
- ▷ *results:* about 80 ± 10 SNU vs. predicted 132 ± 7 SNU (1 SNU: 10^{-36} interactions per target atom/s)

3) *The Sudbury Neutrino Observatory (SNO)*

- ▷ located in a deep mine (2070 m underground)
- ▷ 1000 tons of pure, *heavy water* (D_2O)
- ▷ in acrylic plastic vessel with 9456 light sensors/photo-multiplier tubes
- ▷ detect *Cerenkov radiation* of electrons and photons from weak interactions and neutrino-electron scattering
- ▷ *results (June 2001): confirmation of neutrino oscillations (MSW effect)?*

Star Formation (I)

Orion Nebula



E. STAR FORMATION (ZG: 15.3; CO: 12)

Star-Forming Regions

a) *Massive stars*

- born in *OB associations* in warm molecular clouds
- produce *brilliant HII regions*
- shape their environment
  - ▷ photoionization
  - ▷ stellar winds
  - ▷ supernovae
  - → induce further (low-mass) star formation?

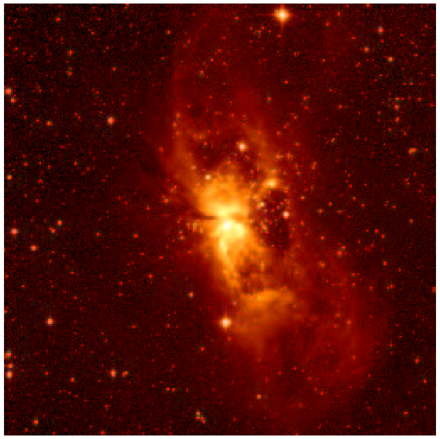
b) *Low-mass stars*

- born in *cold, dark molecular clouds* ($T \simeq 10\,K$)
- Bok globules
- near massive stars?
- *recent:* most low-mass stars appear to be born in *cluster-like environments*
- *but:* most low-mass stars are not found in clusters → embedded *clusters do not survive*

  Relationship between massive and low-mass star formation?

  - ▷ massive stars trigger low-mass star formation?
  - ▷ massive stars terminate low-mass star formation?

Star Formation (II)

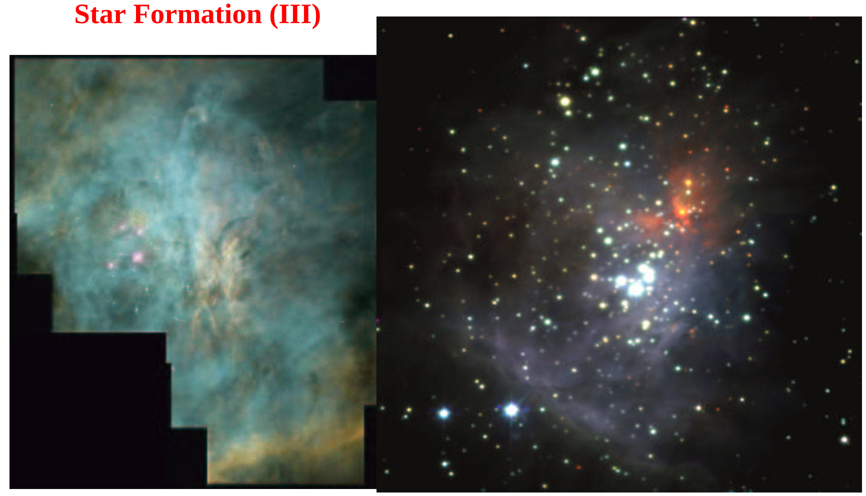


massive star +
cluster of low-mas stars

S 106

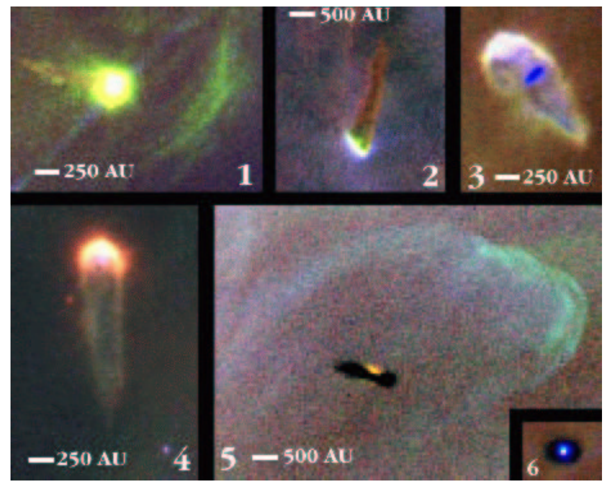
Bok globules

Star Formation (III)

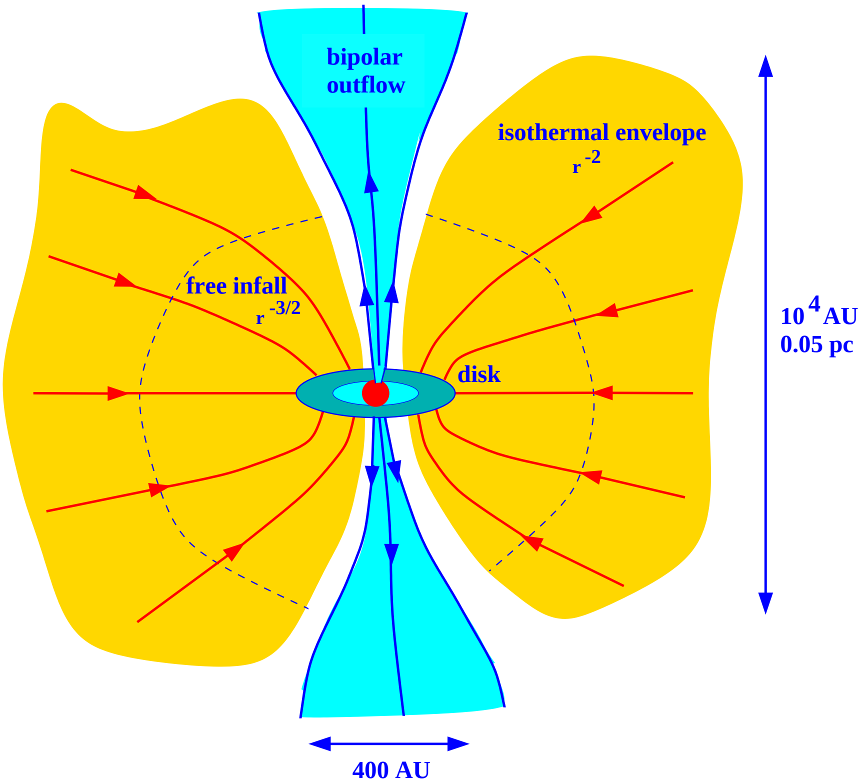


The Trapezium Cluster (IR)

HST



Dusty Disks in Orion (seen as dark silhouettes)

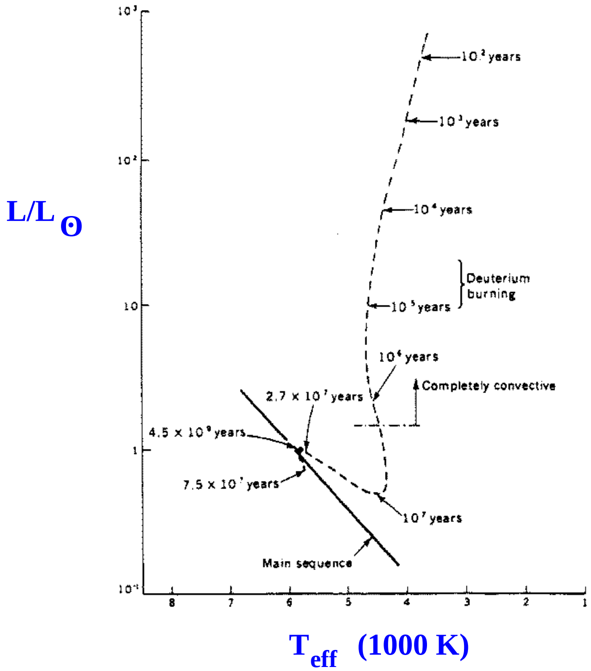


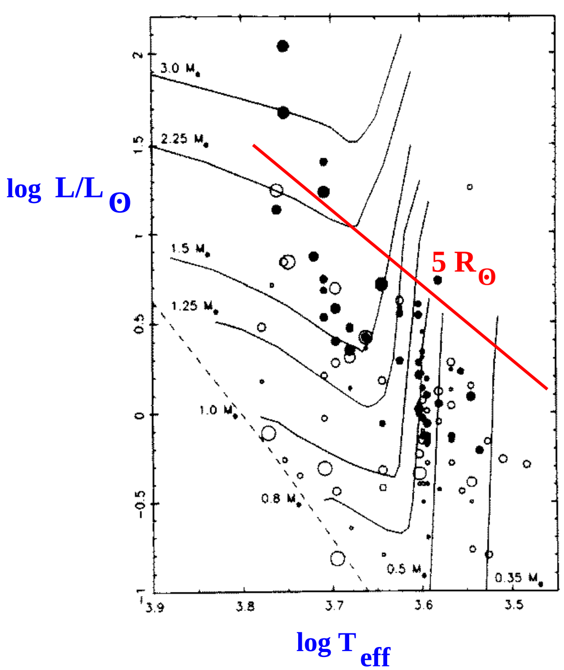
Protostar Structure

Stellar Collapse (Low-mass)

- cool, *molecular cores* (H_2) collapse when their mass exceeds the *Jeans Mass*
  - ▷ no thermal pressure support if $P_c = \rho/(\mu m_H)kT < GM^2/(4\pi R^4)$
  - ▷ or $M > M_J \simeq 6\,M_\odot \left(\frac{T}{10\,K}\right)^{3/2} \left(\frac{n_{H_2}}{10^{10}\,m^{-3}}\right)^{-1/2}$
- collapse triggered:
  - ▷ by *loss of magnetic support*
  - ▷ by *collision* with other cores
  - ▷ by *compression* caused by nearby supernovae
- *inside-out isothermal collapse* (i.e. efficient radiation of energy) from $\sim 10^6\,R_\odot$ to $\sim 5\,R_\odot$
- *timescale:* $t_{dyn} \sim 1/\sqrt{4\,G\rho} \sim 10^5 - 10^6$ yr
- collapse *stops* when material becomes *optically thick* and can no longer remain isothermal *(protostar)*
- *the angular-momentum problem*
  - ▷ each molecular core has a small amount of angular momentum (due to the velocity shear caused by the Galactic rotation)
  - ▷ characteristic $\Delta v/\Delta R \sim 0.3$km/s/ly
  - → characteristic, specific angular momentum $j \sim (\Delta v/\Delta R\, R_{cloud})\, R_{cloud} \sim 3 \times 10^{16}\,m^2\,s^{-1}$
  - ▷ cores cannot collapse directly
  - → formation of an *accretion disk*

Pre-Main-Sequence Evolution





▷ characteristic disk size from angular-momentum conservation $j = rv_\perp = rv_{\rm Kepler} = \sqrt{GMr}$

$\rightarrow r_{\rm min} = j^2/GM \sim 10^4\,R_\odot \simeq 50\,{\rm AU}$

- *Solution:* Formation of *binary systems and planetary systems* which store the angular momentum (Jupiter: 99 % of angular momentum in solar system)

  $\rightarrow$ *most stars should have planetary systems and/or stellar companions*

  $\rightarrow$ stars are initially *rotating rapidly* (spin-down for stars like the Sun by magnetic braking)

- inflow/outflow: $\sim 1/3$ of material accreted is ejected from the accreting protostar $\rightarrow$ bipolar jets

Pre-main-sequence evolution

- Old picture: stars are born with *large radii* ($\sim 100\,R_\odot$) and slowly contract to the main sequence

  ▷ energy source: *gravitational energy*

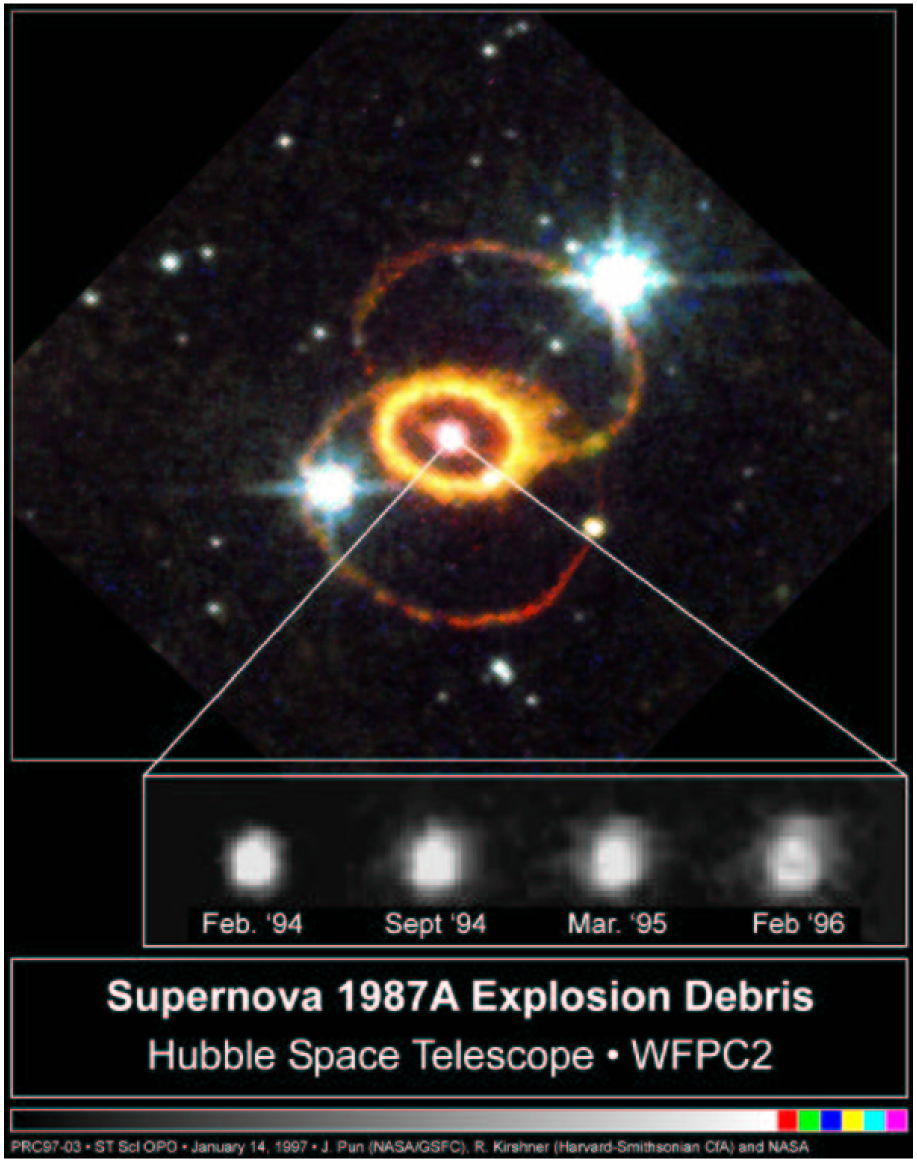
  ▷ contraction stops when the central temperature reaches 10^7 K and H-burning starts (main sequence)

  ▷ note: D already burns at $T_c \sim 10^6$ K $\rightarrow$ temporarily halts contraction

- *Modern picture:* stars are born with *small radii* ($\sim 5\,R_\odot$) and small masses

  $\rightarrow$ first appearance in the H-R diagram on the *stellar birthline* (where accretion timescale is comparable to Kelvin-Helmholtz timescale: $t_{\dot M} \equiv M/\dot M \sim t_{\rm KH} = GM^2/(2RL)$)

  ▷ continued accretion as *embedded protostars/T Tauri stars* until the mass is exhausted or accretion stops because of dynamical interactions with other cores/stars



F. THE TRIPLE-RING NEBULA (Supplementary)

- the material in the nebula was ejected by the *progenitor* $\sim 30,000\,$yr before the supernova

→ extremely non-spherical, but approximately *axi-symmetric*

→ signature of *rotation?*

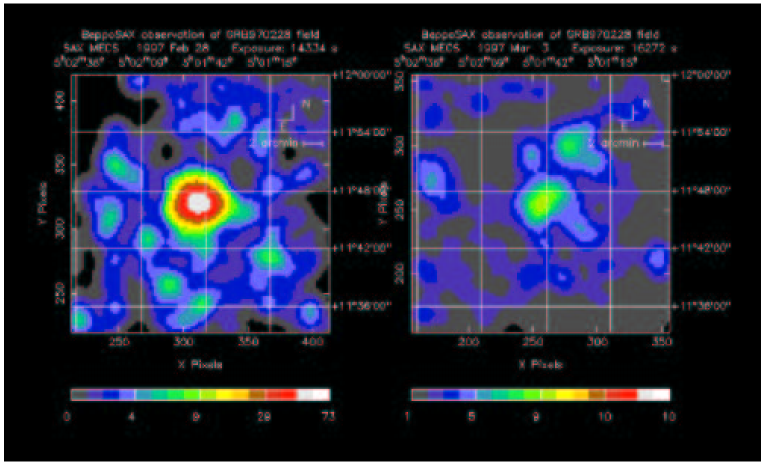
- progenitor was a red supergiant in recent past
- any single star would have to be slowly rotating as a red supergiant even if it was rapidly rotating on the main sequence (because there is no source of angular momentum and the star expands by a factor of ~ 100)

→ *signature of a binary*

Model

- *progenitor* was a wide *binary* that *merged 30,000 yr* ago
  - → source of angular momentum → *triple-ring nebula*
  - → mixing + addition of mass → *blue supergiant*
  - → *chemical anomalies*
- *jet-like explosion because of rapidly rotating core?*

Gamma-Ray Bursts



Beppo-Sax X-ray detection

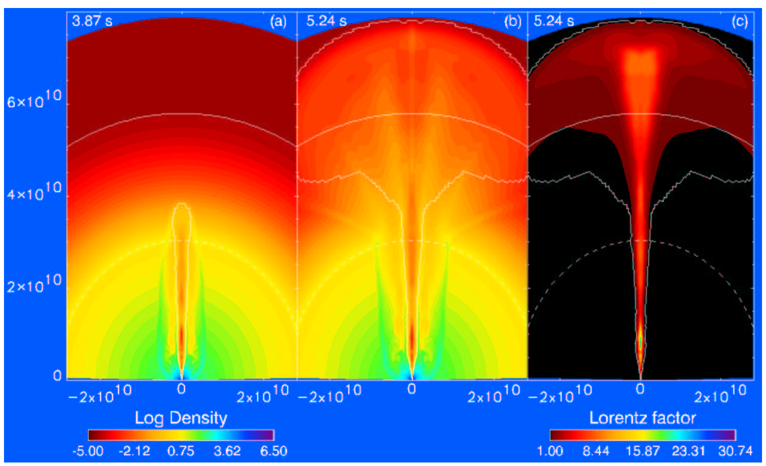


FIG. 1.— Contour maps of the logarithm of the rest–mass density after 3.87 s and 5.24 s (left two panels), and of the Lorentz factor (right panel) after 5.24 s. X and Y axis measure distance in centimeters. Dashed and solid arcs mark the stellar surface and the outer edge of the exponential atmosphere, respectively. The other solid line encloses matter whose radial velocity $> 0.3c$, and whose specific internal energy density $> 5 \times 10^{19}$ erg g^{-1}.

Collapsar Model for GRBs

G. GAMMA-RAY BURSTS (ZG: 16-6; CO: 25.4)

- *discovered* by U.S. *spy satellites* (1967; secret till 1973)
- have remained one of the biggest mysteries in astronomy until 1998 (*isotropic* sky distribution; location: solar system, Galactic halo, distant Universe?)
- *discovery of afterglows* in 1998 (X-ray, optical, etc.) with *redshifted absorption lines* has resolved the puzzle of the location of GRBs → *GRBs are the some of the most energetic events in the Universe*
- *duration:* 10^{-3} to 10^{3} s (large variety of burst shapes)
- *bimodal* distribution of *durations:* 0.3 s (short-hard), 20 s (long-soft) (different classes/viewing angles?)
- GRBs are *no* standard candles! (isotropic) energies range from 5×10^{44} to 2×10^{47} J
- *highly relativistic outflows (fireballs):* ($\gamma \gtrsim 100$,) possibly highly *collimated/beamed*
- GRBs are produced far from the source ($10^{11} - 10^{12}$ m): interaction of outflow with surrounding medium (external or internal shocks) → *fireball model*
- *relativistic energy* $\sim 10^{46} - 10^{47}$ J $\epsilon^{-1} f_{\Omega}$ (ϵ: efficiency, f_{Ω}: beaming factor; typical energy 10^{45} J?)
- *event rate/Galaxy:* $\sim 10^{-7}\,\mathrm{yr}^{-1}\,(3 \times 10^{45}\,\mathrm{J}/\epsilon\,\mathrm{E})$

Popular Models

- *merging compact objects* (two NS's, BH+NS) → can explain short-duration bursts
- *hypernova* (very energetic supernova associated with formation of a rapidly rotating *black hole*) → *jet penetrates stellar envelope* → GRB along jet axis (large beaming)

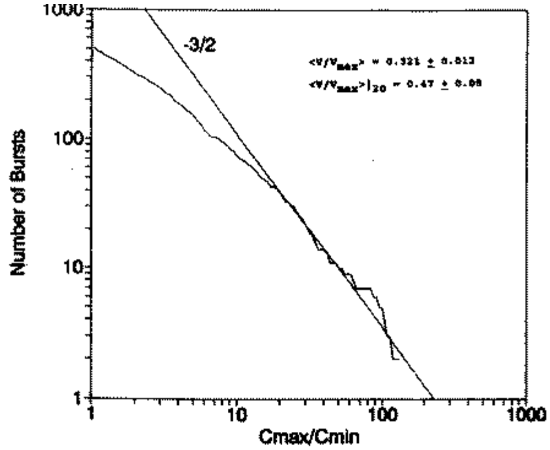


Figure 4. Intensity distribution for BATSE bursts. The measure of intensity is the maximum count rate divided by the threshold count rate.

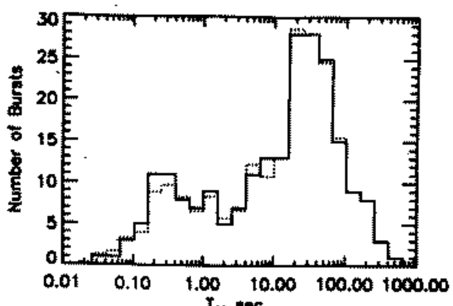


Figure 7. The duration distribution for 222 BATSE bursts, as measured by T_{90}. The solid histogram represents the raw data; the dashed histogram represents the data convolved with measurement errors.

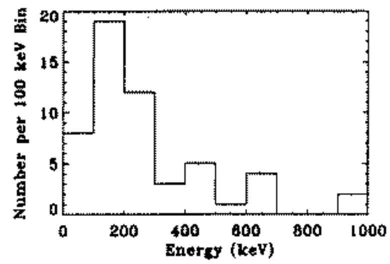


Figure 8. The distribution of the energy of the peak emission per ı logarithmic energy interval.

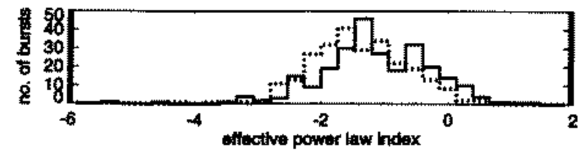


Figure 9. The distribution of burst spectral indices in the 50 to 300 keV ergy band. The solid line represents the distribution for the peak rate spectr and the dotted line represents the distribution for the total fluence spectrum

Meegan et al. (1994)