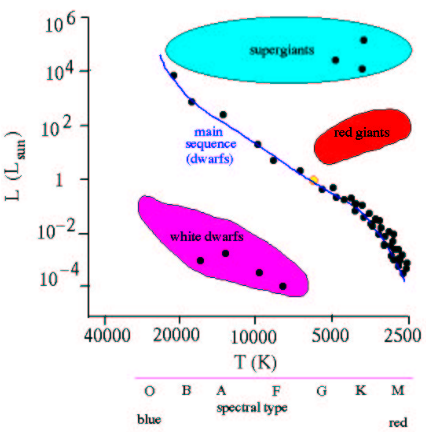
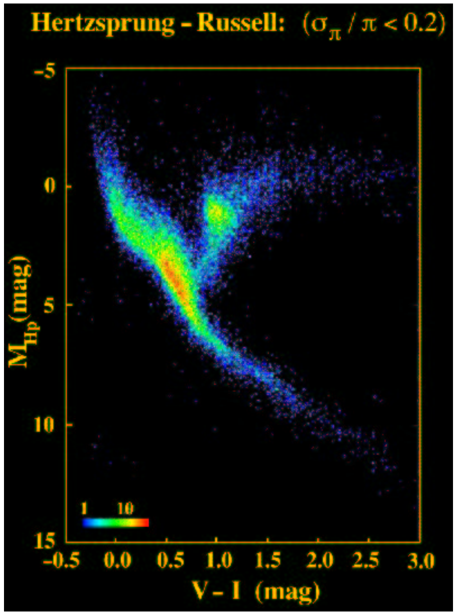
Hertzsprung-Russell (Colour-Magnitude) Diagram





Hipparcos (1989 - 1993)

Correlations between Stellar Properties

Mass-luminosity relationship:

- Most stars obey

$$L_s = constant \times M_s^{\nu} \qquad 3 < \nu < 5$$

- *Hertzsprung–Russell diagram* (plot of L_s vs. T_{eff}): and *Colour–Magnitude Diagram* (e.g. plot of V vs. B-V) From diagram for nearby stars of known distance we deduce:

  1. About 90% of stars lie on the main sequence (broad band passing diagonally across the diagram)
  2. Two groups are very much more luminous than MS stars (giants and supergiants)
  3. One group is very much less luminous; these are the white dwarfs with $R_s << R_\odot$ but $M_s \sim M_\odot$.

- log g – log T_{eff} diagram, determined from atmosphere models (does not require distance)

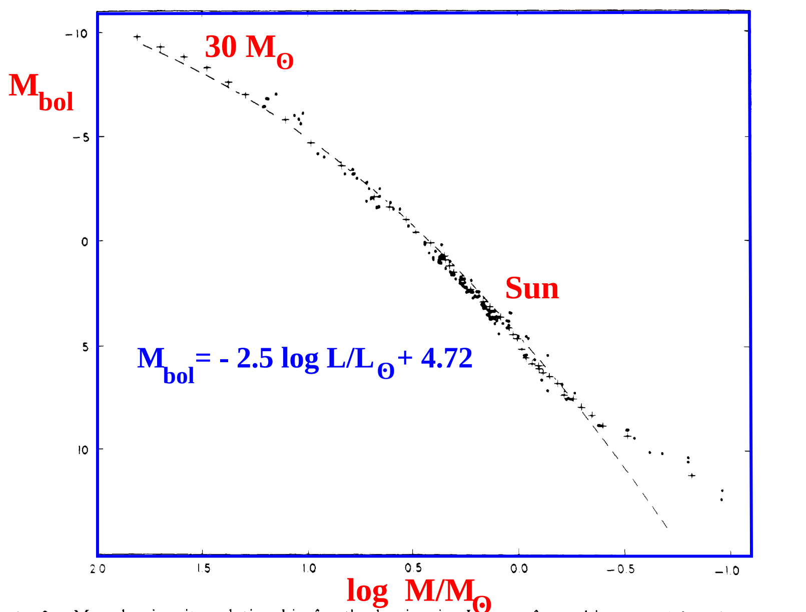


Fig. 2. Mass-luminosity relationship for the luminosity V stars from this paper (plus signs), from Popper (1980) (points) and from Heintze (1973) (broken line).

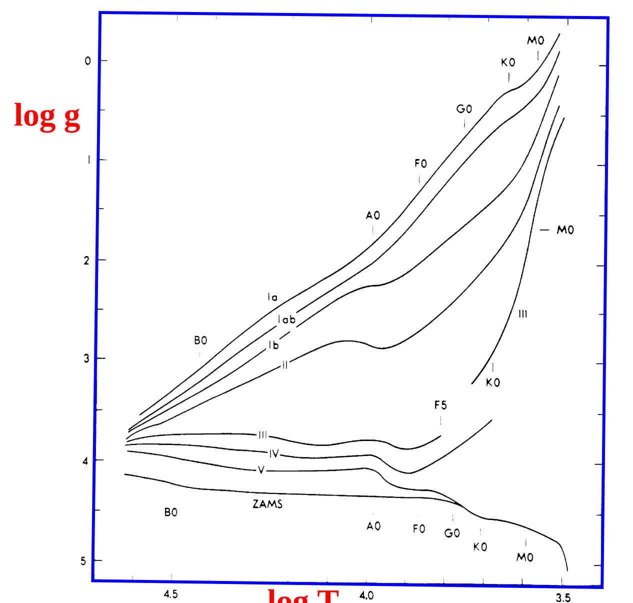


Fig. 3. The diagram log g, log T, for stars of different luminosities plotted from the data of Tab

Cluster H-R Diagrams

- *Galactic or open clusters* – 10 to 1000 stars, not concentrated towards centre of cluster – found only in *disc of Galaxy*
- *Globular clusters* – massive spherical associations containing 10^5 or more stars, *spherically distributed* about centre of Galaxy, many at great distances from plane.
- All stars within a given cluster are effectively *equidistant* from us; we are probably seeing *homogeneous, coeval* groups of stars, and with the *same chemical composition.* We can construct *H-R diagrams* of apparent brightness against temperature.

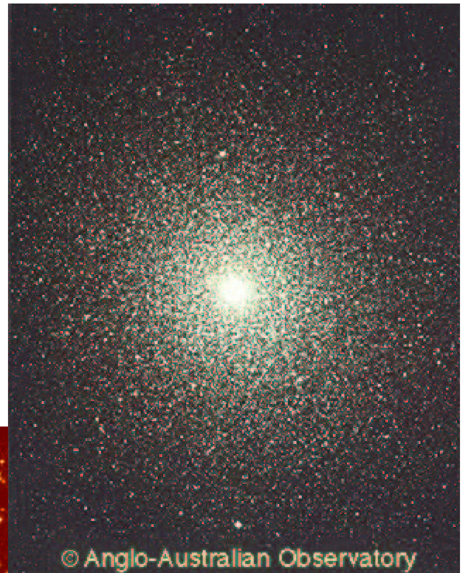
Main features of H-R diagrams:

1. *Globular clusters*
   (a) All have *main sequence turn-off* in similar position and giant branch joining main sequence at that point.
   (b) All have *horizontal branch* running from near top of giant branch to main sequence above turn-off point.
   (c) In many clusters *RR Lyrae stars* (variable luminosity) occupy a region of the horizontal branch.
2. *Galactic clusters*
   (a) Considerable variation in MS turn-off point; lowest in about same position as that of globular clusters.
   (b) Gap between MS and giant branch *(Hertzsprung gap)* in clusters with high turn-off point.

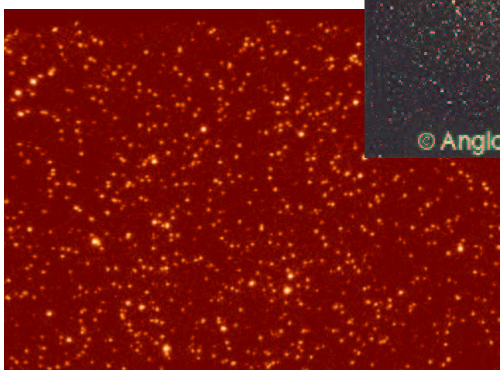
STAR CLUSTERS

Open Cluster (Pleiades)

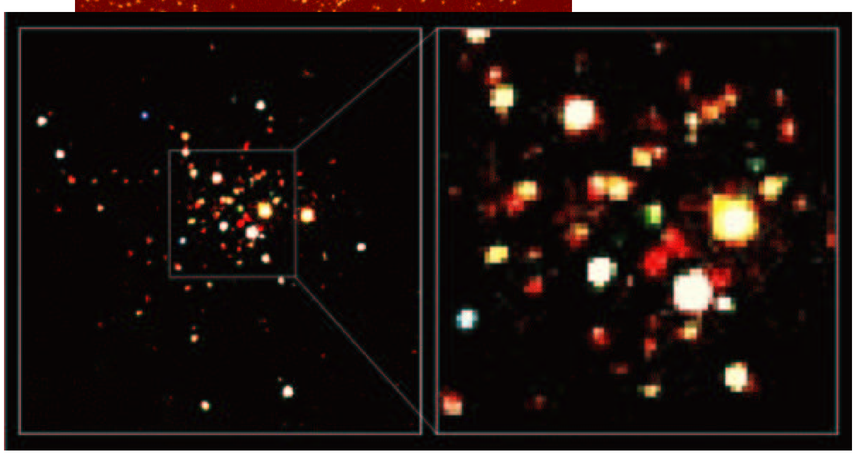
Globular Cluster (47 Tuc)



HST

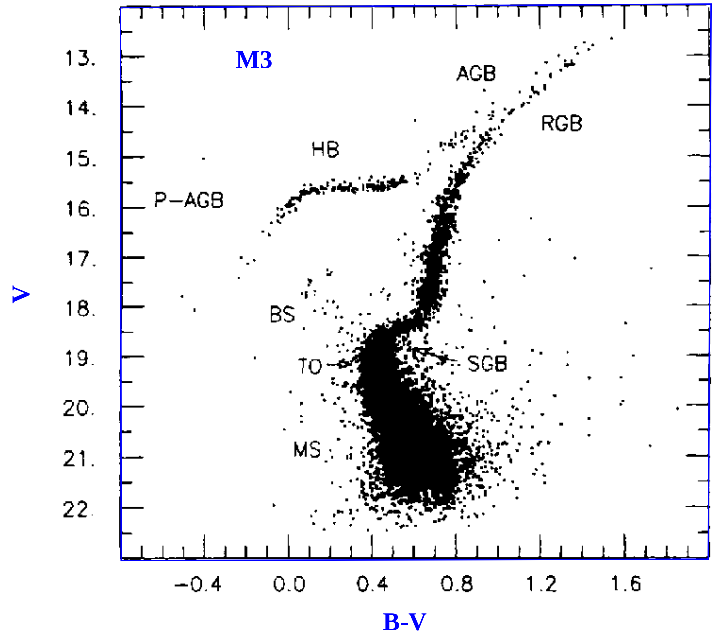


47 Tucanae

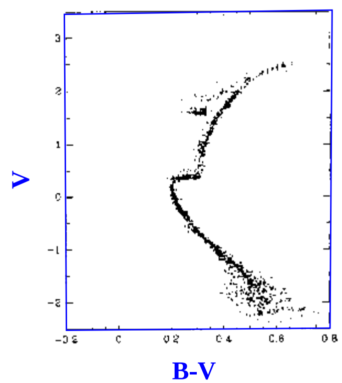


Chandra (X-rays)

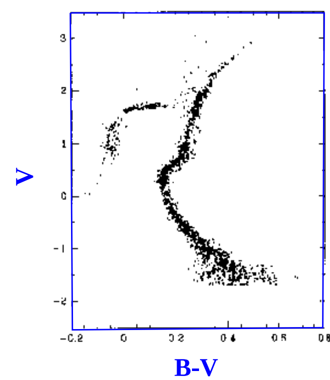
Globular Cluster CM Diagrams



47 Tuc



M15



Chemical Composition of Stars

- We deduce the *photospheric composition* by studying *spectra:* information often incomplete and of doubtful precision.
- *Solar system* abundances: Reasonable agreement between analysis of solar spectrum and laboratory studies of meteorites (carbonaceous chondrites).
- *Normal stars* (vast majority): Similar composition to Sun and interstellar medium
  Typically: *Hydrogen 90% by number; Helium 8%; other elements (metals)* $\ll 1\,\%$
  (by mass: $X \simeq 0.70$, $Y \simeq 0.28$, $Z \simeq 0.02$)
- *Globular cluster stars: Metal deficient* compared to Sun by factors of $10 - 1000$,
  Hydrogen and helium normal

Assuming uniform initial composition for the Galaxy, we conclude that about 99% of metals must have been synthesized within stars.

THIS IS THE PRIMARY EVIDENCE FOR NUCLEOSYNTHESIS DURING STELLAR EVOLUTION.

- *Very metal deficient stars:* A few very faint stars have been discovered in the Galactic halo which are metal deficient compared to the Sun by a factor of about 10,000 (first generation of stars?).

STELLAR POPULATIONS

Population I: metallicity: $Z \sim 0.02$ (i.e. solar), old and young stars, mainly in the Galactic disc, open clusters

Population II: metallicity: $Z \sim 0.1 - 0.001\,Z_\odot$, old, high-velocity stars in the Galactic halo, globular clusters

Population III: hypothetical population of zero-metallicity stars (first generation of stars?), possibly with very different properties (massive, leading to relatively massive black holes?), may not exist as a separate population

Stars with peculiar surface composition:

- Most stars seem to retain their initial surface composition as the centre evolves. A small number show anomalies, which can occur through:
  1) *mixing* of central material to the surface
  2) large scale *mass loss* of outer layers exposing interior.
  3) *mass transfer* in a binary (e.g. barium stars)
  4) pollution with *supernova* material from a binary companion (e.g. Nova Sco)

  a) Helium stars: Systematic increase of He abundance over normal stars; n(He) >> n(H) in extreme cases.

b) Carbon stars: **Red-giant stars showing anomalously large surface abundance of carbon, either in atomic or molecular form**

- ▷ **CH, CN isotope shift between bands arising from ^{13}C can sometimes be resolved.**
- ▷ **In some carbon stars $n(^{12}C)/n(^{13}C) \sim 100$ i.e. solar value. In many carbon stars $n(^{12}C)/n(^{13}C) \sim 5$.**

This is evidence for a particular sequence of nuclear reactions (CNO cyle).

c) Barium stars: **Particularly strong Ba lines; elements with $Z > 35$ overabundant by order of magnitude relative to the Sun *(s-process).***

d) S stars **Very cool red giants showing strong bands of ZrO, LaO, YO plus corresponding atomic lines.**

- ▷ **In 1952, lines of Tc discovered in S-star spectra (isotopes of Tc are radioactive with half-life $< 10^6$ yr); hence all traces of original Tc should have disappeared).**

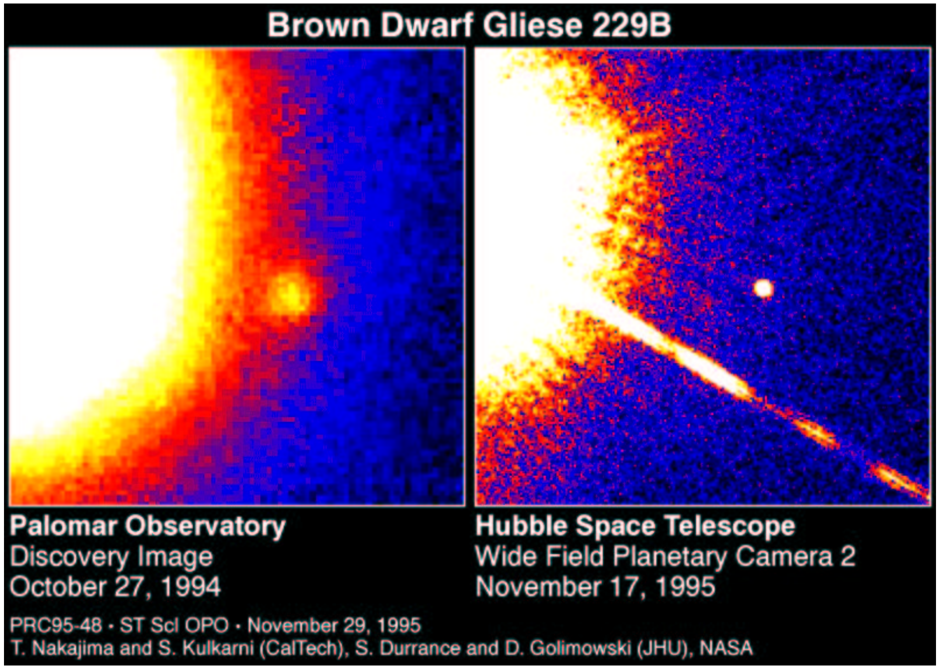
e) FG Sagittae:

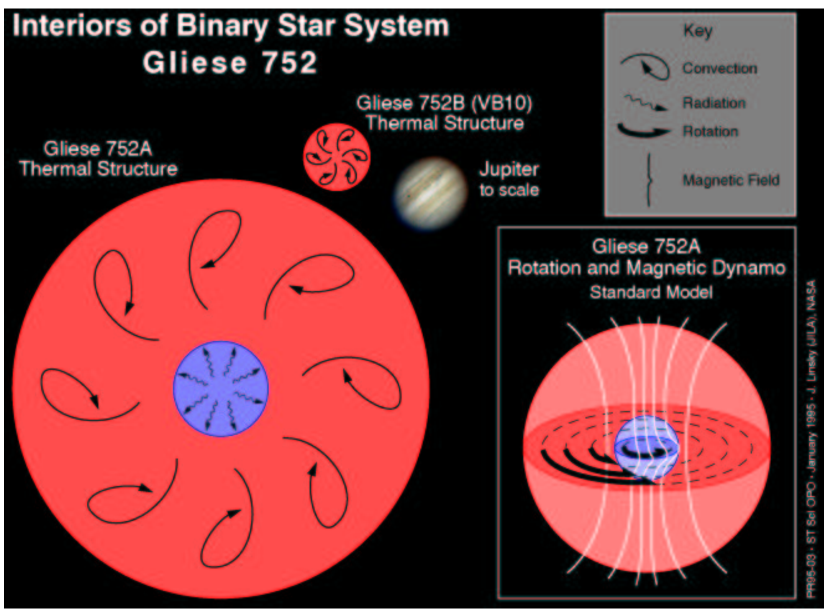
- ▷ **Only star known in which contamination of atmosphere by products of *nuclear processing* has proceeded on *short (human) time-scale.***
- ▷ **Supergiant star, $T_{eff} \sim 6500$ K, cooling at 250 K per year around 1970.**
- ▷ **Abnormally *strong lines of Y, Zr, Ce, La* began to appear in 1967 and have progressively strengthened. By 1974, abundances of these elements were about 25 times solar.**

This stage of evolution must occur very rapidly on a cosmic time-scale and hence is difficult to observe.

Brown Dwarfs

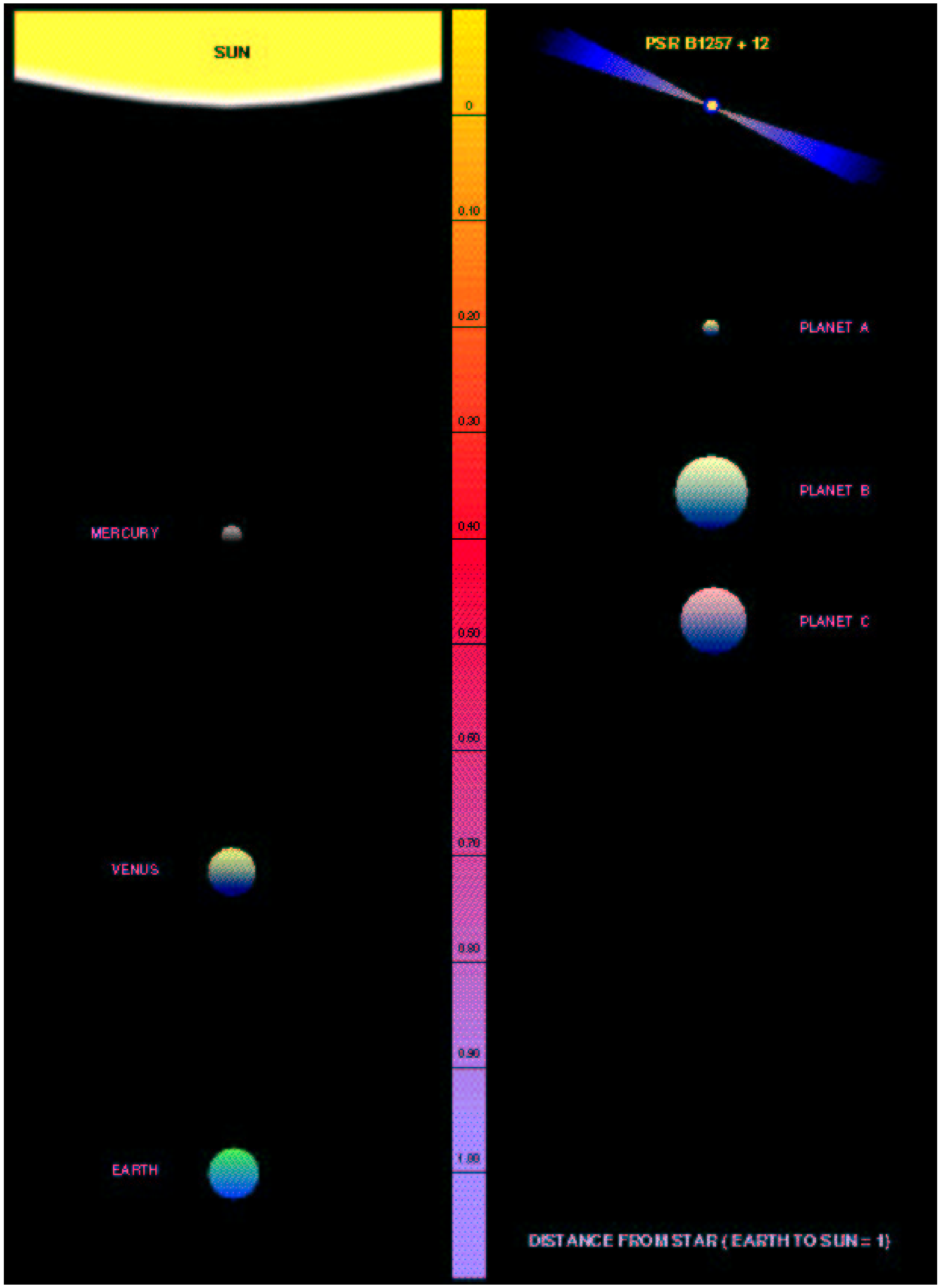
- **star-like bodies with *masses too low* to create the central temperature required *to ignite fusion reactions* (i.e. $M \lesssim 0.08\,M_\odot$ from theory).**
- **reach maximum temperature by gravitational contraction and then cool steadily becoming undetectable, with surface temperature less than 1000 K, after a few billion years (stars with $T_{eff} < 2000$ 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 $T_{eff} < 1500$ 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 $T_{eff} < 2000$ K.**
- ***Missing Mass:* Detections so far indicate that Brown Dwarfs are *not sufficiently abundant* to account significantly *for the missing mass.***

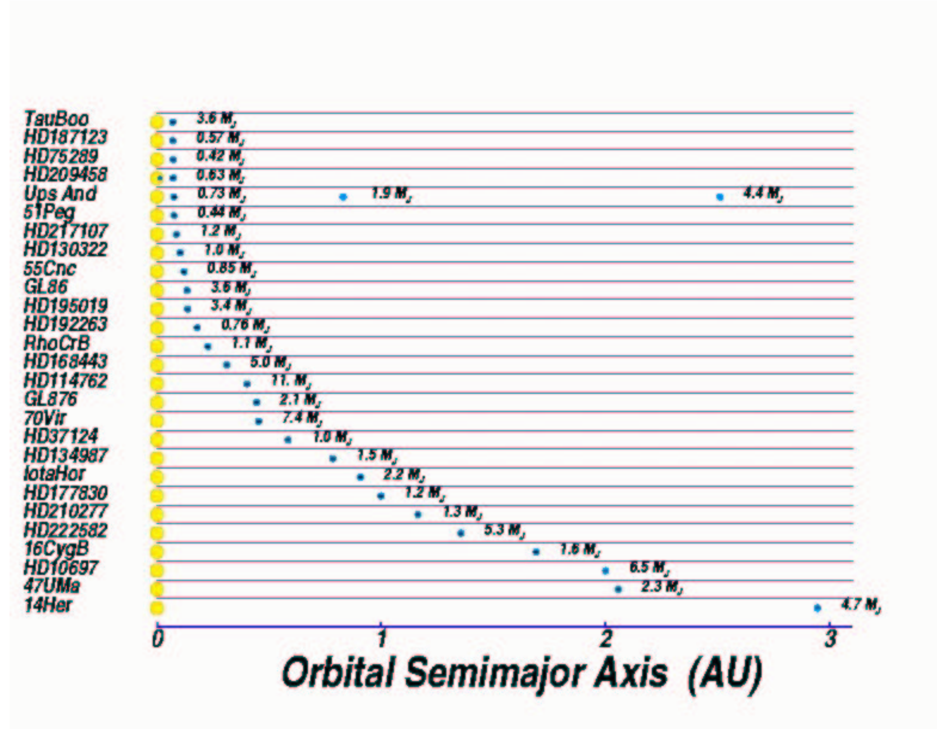




Extrasolar Planets

- 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 $> 0.015\,\mathrm{M}_\oplus$, (25 d), $> 3.4\,\mathrm{M}_\oplus$ (66 d), $> 2.8\,\mathrm{M}_\oplus$ (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 $>> \mathrm{M}_{\mathrm{Jup}}$) have been discovered around normal stars


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


TauBoo
HD187123
HD75289
HD209458
Ups And
51Peg
HD217107
HD130322
55Cnc
GL86
HD195019
HD192263
RhoCrB
HD168443
HD114762
GL876
70Vir
HD37124
HD134987
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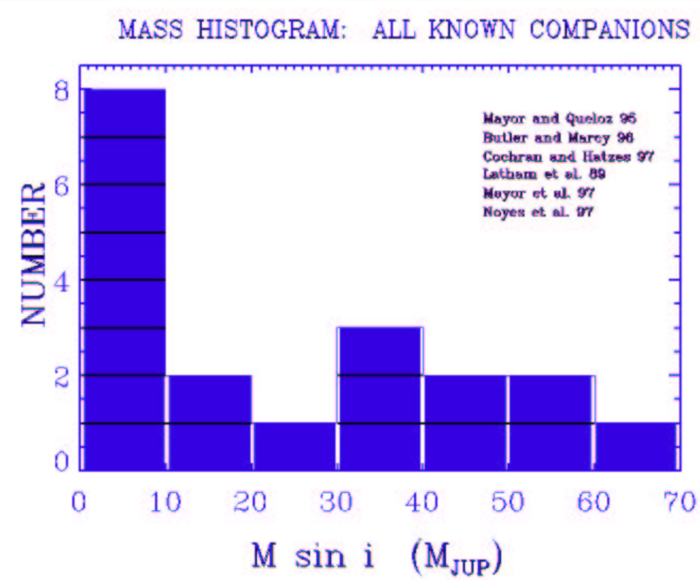
HD177830
HD210277
HD222582
16CygB
HD10697
47UMa
14Her
Orbital Semimajor Axis (AU)


MASS HISTOGRAM: ALL KNOWN COMPANIONS
Mayor and Queloz 95
Butler and Marcy 96
Cochran and Hatzes 97
Latham et al. 89
Mayor et al. 97
Noyes et al. 97
NUMBER
M sin i (M_JUP)

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).**