A science overview of optical interferometry

Francesco Paresce

Abstract

The accurate determination of fundamental stellar parameters (diameter, effective temperature, mass, distance) by optical/IR interferometry and how this will affect our knowledge of stellar astrophysics.

Interferometric studies of circumstellar matter

Rens Waters

Abstract

Circumstellar matter plays an important role in the formation and the late phases of evolution of stars. In the star formation process, observations of the geometry and physical conditions in the proto-stellar cloud are needed to constrain star and planet formation models. One of the key issues in this field is the structure of the circumstellar disk, which forms around young stars as a result of the conservation of angular momentum. High angular resolution observations are needed to resolve the inner disk structure. In the final stages of stellar evolution, both massive stars as well as low mass stars go through a phase of extensive mass loss, through a dense, dusty, and slowsy expanding wind. The physics of this wind is poorly understood, but is of importance for stellar evolution: mass loss virtually terminates the evolution by the removal of the entire hydrogen-rich envelope of the star. The processes that govern the formation of dust, the interplay of dust formation with pulsation, and the geometry of the wind, are important points to be clarified, and require high angular resolution imaging. The lecture will address the potential of interferometry, particularly at near-IR and mid-IR wavelengths, to address these issues.

Related publications :

- the Proceedings of the ESO Astrophysics Symposium “Science with the VLTI” ed. F.Paresce, Springer, 1997 and
- the Proceedings of the conference “Working on the fringe” , eds. S.Unwin and R.Stachnik, ASO COnf.Ser., Vol.194

Science overview of Optical/IR Interferometry

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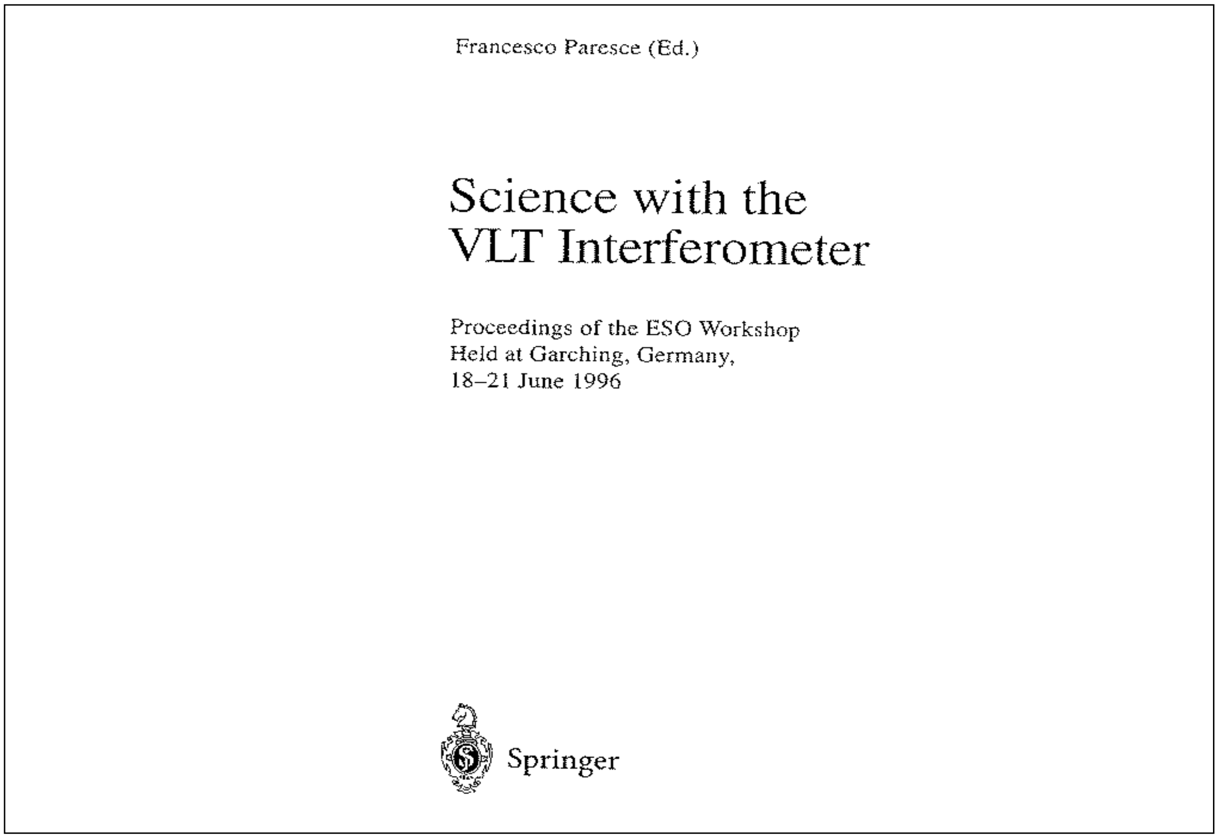
Leiden School of Interferometry

Leiden, September 19,2000

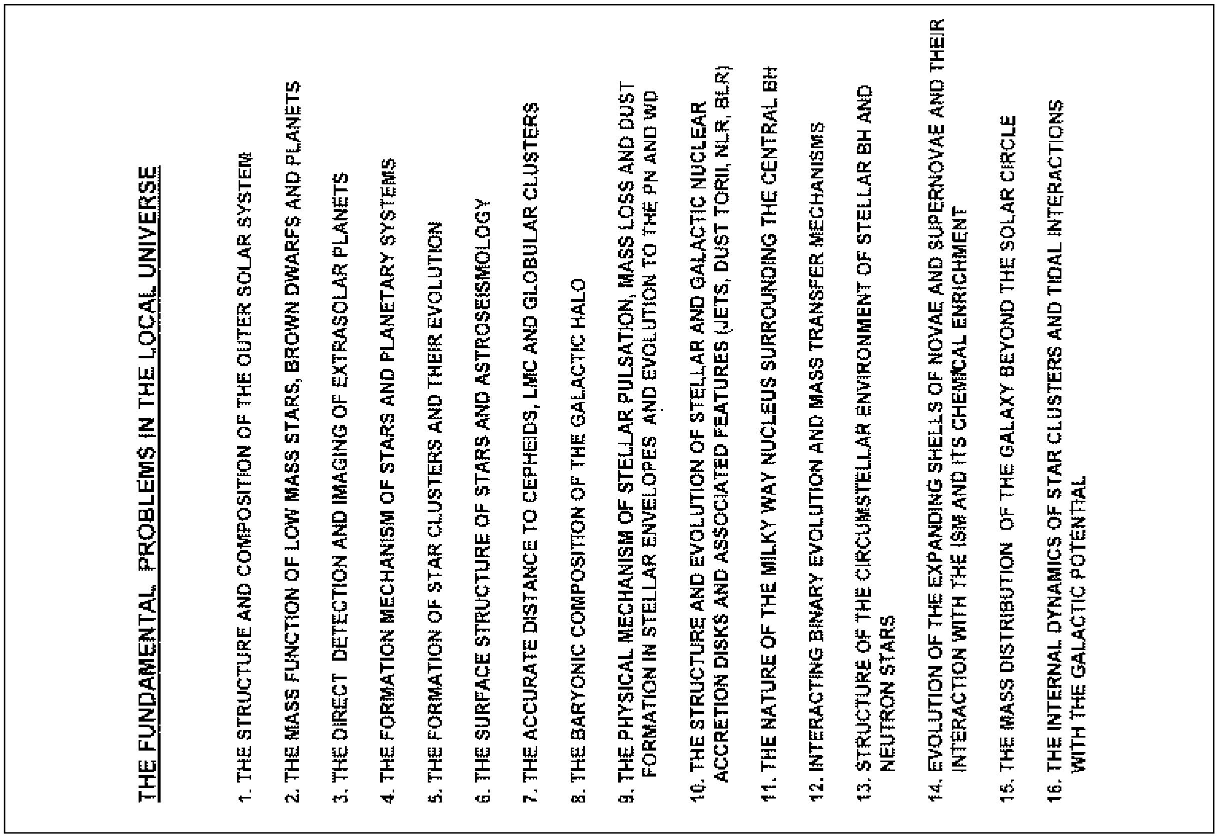


Francesco Paresce (Ed.)

Science with the
VLT Interferometer

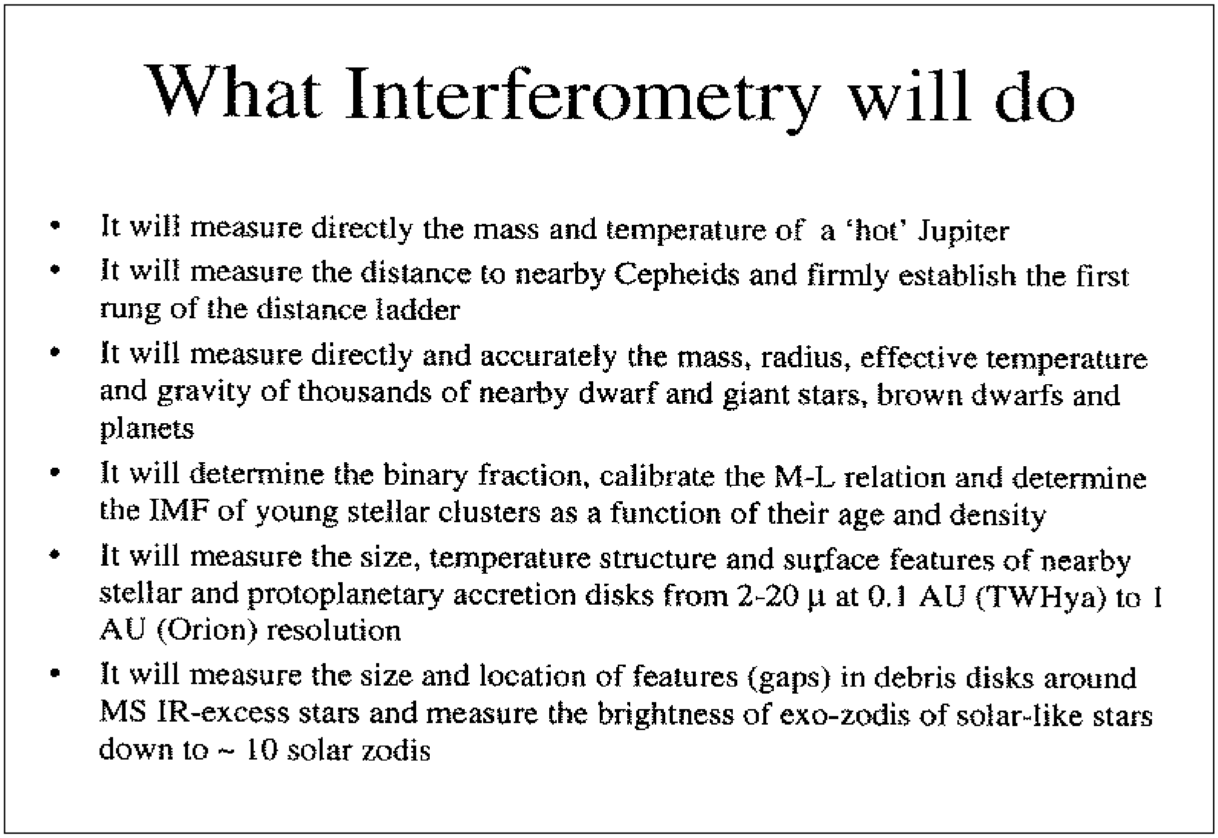
Proceedings of the ESO Workshop
Held at Garching, Germany,
18–21 June 1996

Springer



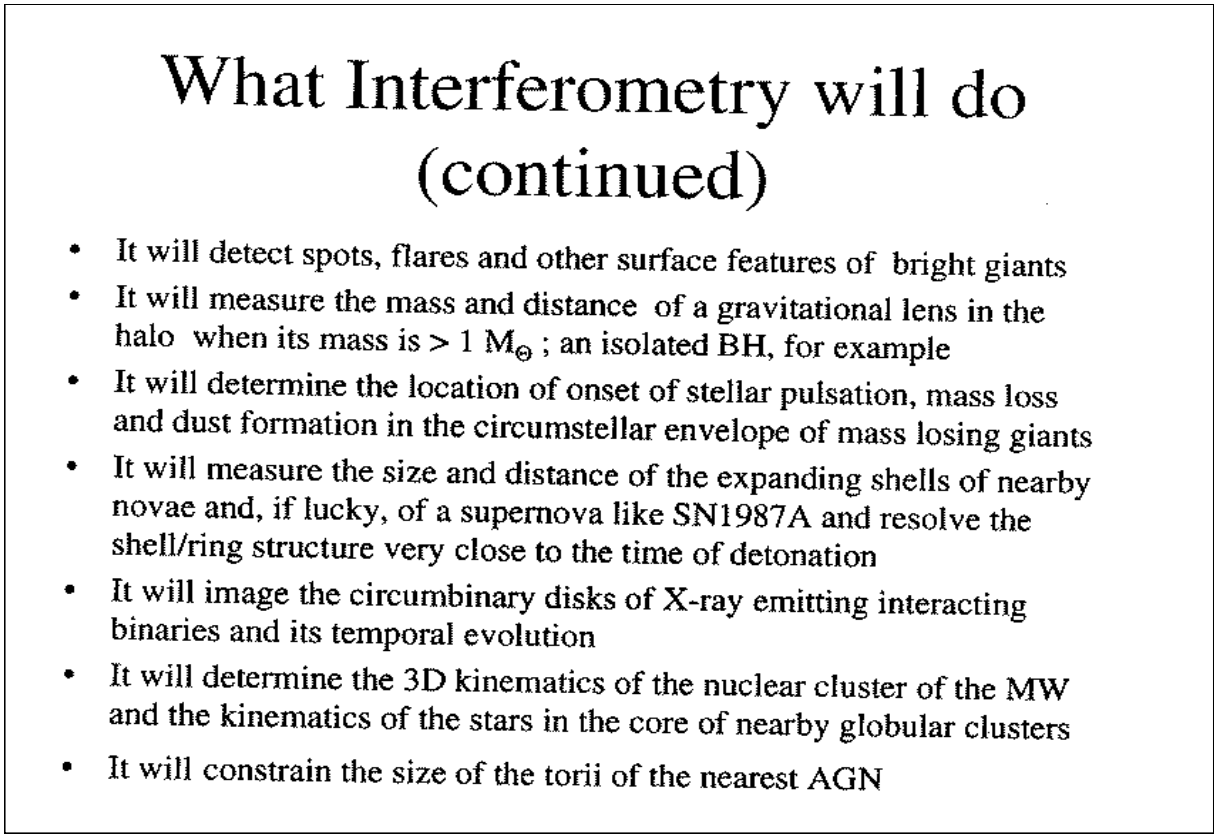
THE FUNDAMENTAL PROBLEMS IN THE LOCAL UNIVERSE

1. THE STRUCTURE AND COMPOSITION OF THE OUTER SOLAR SYSTEM
2. THE MASS FUNCTION OF LOW MASS STARS, BROWN DWARFS AND PLANETS
3. THE DIRECT DETECTION AND IMAGING OF EXTRASOLAR PLANETS
4. THE FORMATION MECHANISM OF STARS AND PLANETARY SYSTEMS
5. THE FORMATION OF STAR CLUSTERS AND THEIR EVOLUTION
6. THE SURFACE STRUCTURE OF STARS AND ASTROSEISMOLOGY
7. THE ACCURATE DISTANCE TO CEPHEIDS, LMC AND GLOBULAR CLUSTERS
8. THE BARYONIC COMPOSITION OF THE GALACTIC HALO
9. THE PHYSICAL MECHANISM OF STELLAR PULSATION, MASS LOSS AND DUST FORMATION IN STELLAR ENVELOPES AND EVOLUTION TO THE PN AND WD
10. THE STRUCTURE AND EVOLUTION OF STELLAR AND GALACTIC NUCLEAR ACCRETION DISKS AND ASSOCIATED FEATURES (JETS, DUST TORII, NLR, BLR)
11. THE NATURE OF THE MILKY WAY NUCLEUS SURROUNDING THE CENTRAL BH
12. INTERACTING BINARY EVOLUTION AND MASS TRANSFER MECHANISMS
13. STRUCTURE OF THE CIRCUMSTELLAR ENVIRONMENT OF STELLAR BH AND NEUTRON STARS
14. EVOLUTION OF THE EXPANDING SHELLS OF NOVAE AND SUPERNOVAE AND THEIR INTERACTION WITH THE ISM AND ITS CHEMICAL ENRICHMENT
15. THE MASS DISTRIBUTION OF THE GALAXY BEYOND THE SOLAR CIRCLE
16. THE INTERNAL DYNAMICS OF STAR CLUSTERS AND TIDAL INTERACTIONS WITH THE GALACTIC POTENTIAL



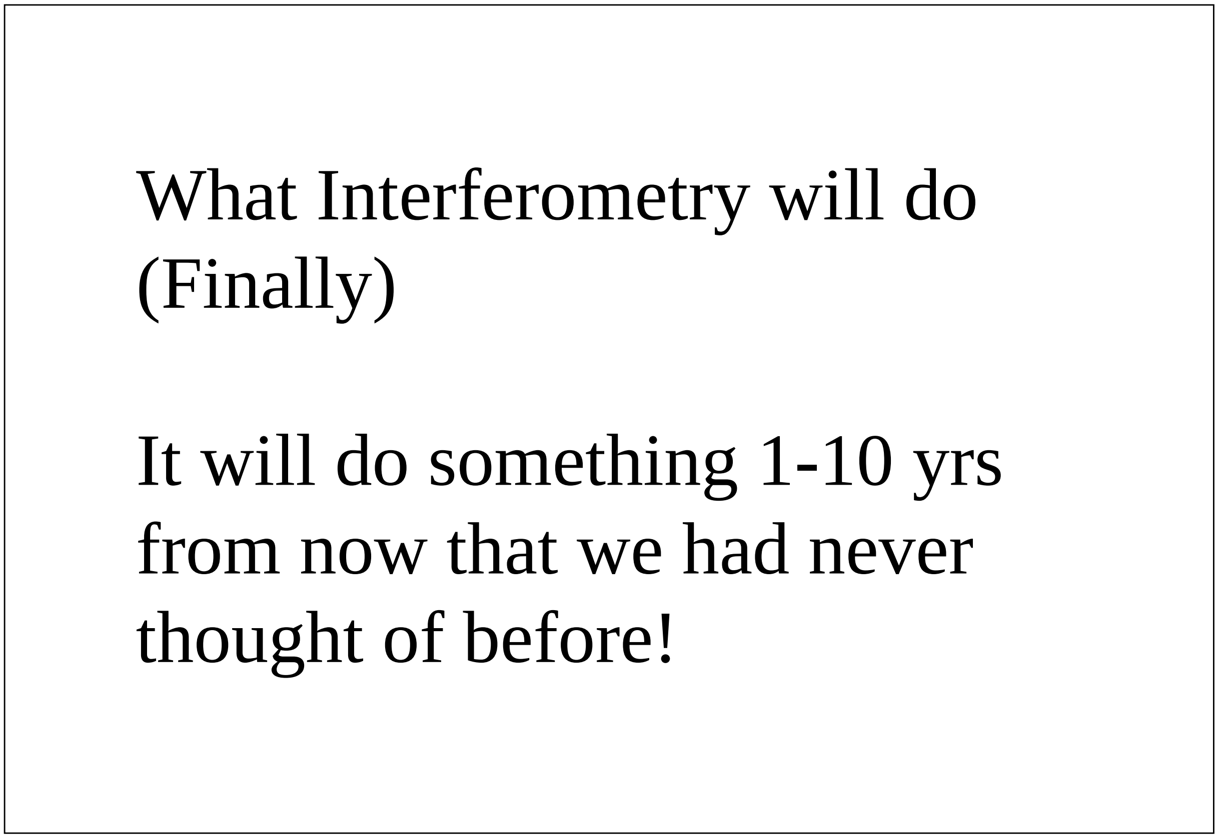
What Interferometry will do

- It will measure directly the mass and temperature of a 'hot' Jupiter
- It will measure the distance to nearby Cepheids and firmly establish the first rung of the distance ladder
- It will measure directly and accurately the mass, radius, effective temperature and gravity of thousands of nearby dwarf and giant stars, brown dwarfs and planets
- It will determine the binary fraction, calibrate the M-L relation and determine the IMF of young stellar clusters as a function of their age and density
- It will measure the size, temperature structure and surface features of nearby stellar and protoplanetary accretion disks from 2-20 μ at 0.1 AU (TWHya) to 1 AU (Orion) resolution
- It will measure the size and location of features (gaps) in debris disks around MS IR-excess stars and measure the brightness of exo-zodis of solar-like stars down to ~ 10 solar zodis



What Interferometry will do (continued)

- It will detect spots, flares and other surface features of bright giants
- It will measure the mass and distance of a gravitational lens in the halo when its mass is > 1 $M_\odot$; an isolated BH, for example
- It will determine the location of onset of stellar pulsation, mass loss and dust formation in the circumstellar envelope of mass losing giants
- It will measure the size and distance of the expanding shells of nearby novae and, if lucky, of a supernova like SN1987A and resolve the shell/ring structure very close to the time of detonation
- It will image the circumbinary disks of X-ray emitting interacting binaries and its temporal evolution
- It will determine the 3D kinematics of the nuclear cluster of the MW and the kinematics of the stars in the core of nearby globular clusters
- It will constrain the size of the torii of the nearest AGN

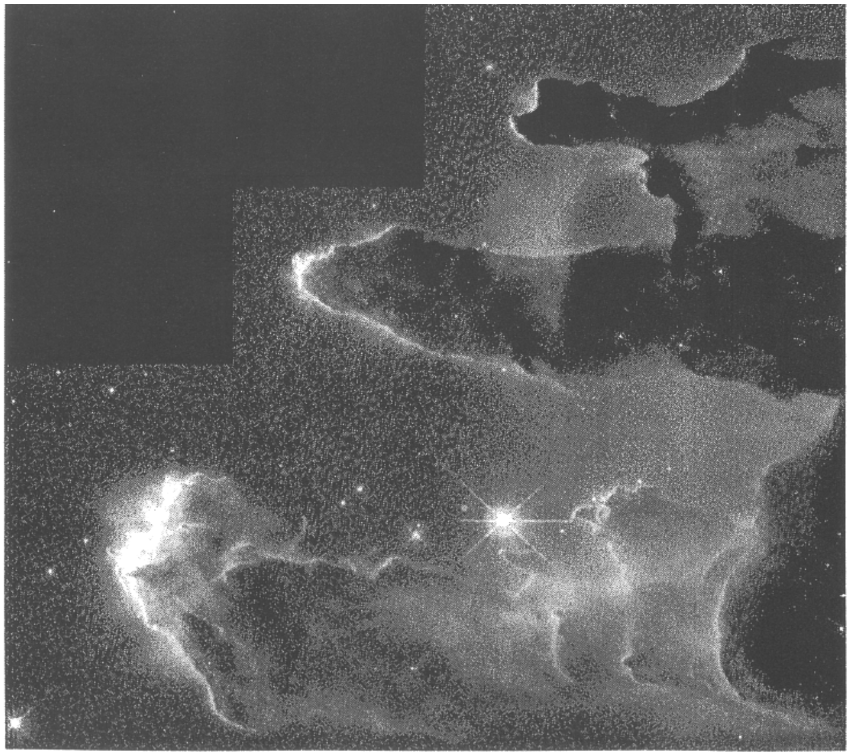


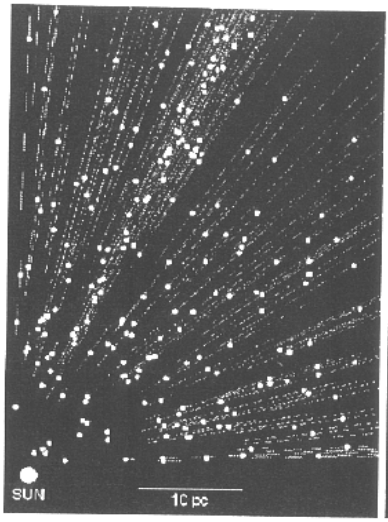
What Interferometry will do (Finally)

It will do something 1-10 yrs from now that we had never thought of before!

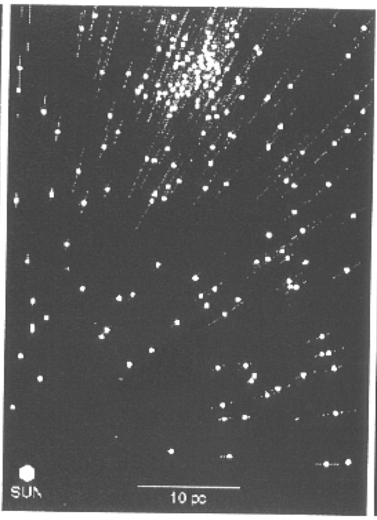
What Interferometry won't do

- It won't reach the edge of the Universe
- It won't reach the Schwarzschild radius of the black hole at the center of the galaxy
- It won't cover vast regions of sky in a survey mode
- It won't deliver megapixel images of a planet or a distant galaxy nucleus
- It won't discover the first star or galaxy





PRE- HIPPARCOS



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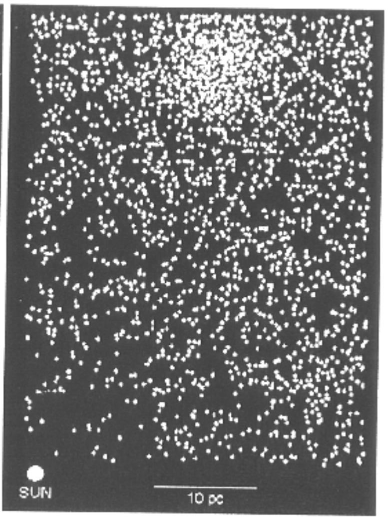
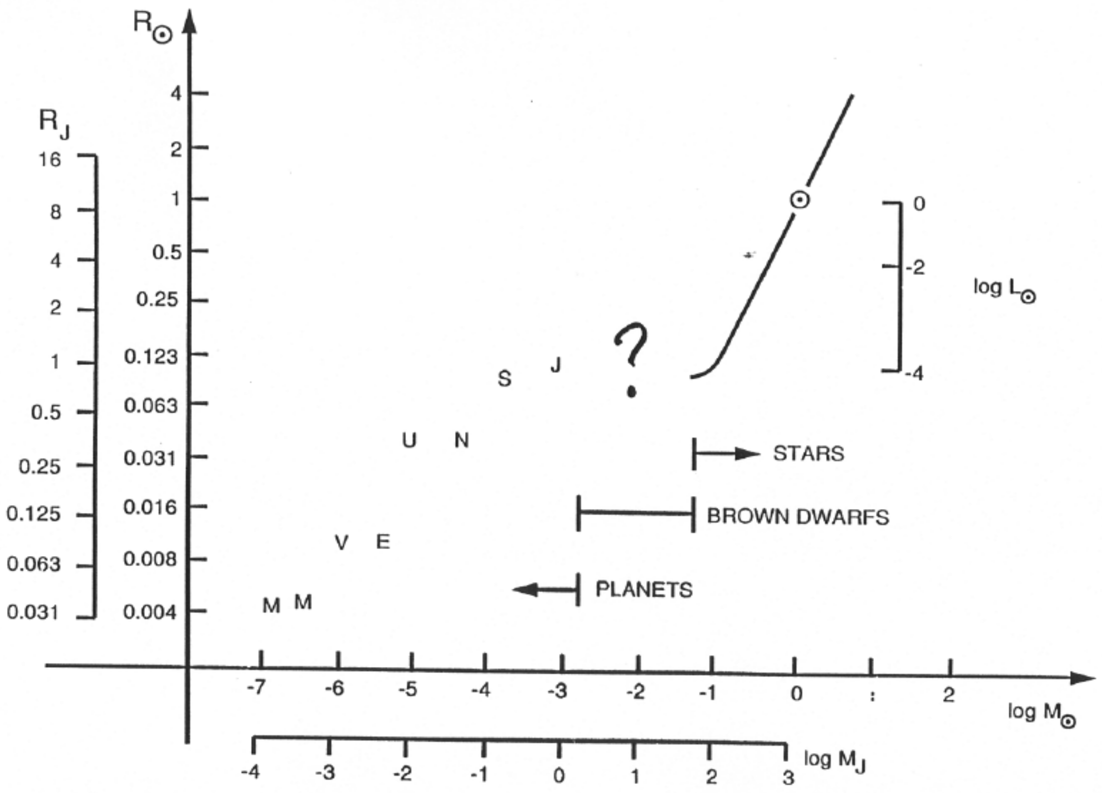


GAIA (EXP.)

Fundamental Stellar Parameters and the VLTI

- We currently need:
  1) <u>accurate</u> values of M, R, T_e, g and [Fe/H] for individual objects (T_e at $2\sigma = +/- 50K$)
  2) general statistics of populations: binary fractions, mass and luminosity functions, IMF etc
- Everywhere on the HR diagram but need is especially acute at the lower end (low mass stars, brown dwarfs, planets etc) and for PMS objects in star forming regions where objects are small ($R < 1\ R_\odot$) and faint ($L < 0.1 L_\odot$)
- VLTI capabilities, therefore, are ideal: high spatial resolution with high sensitivity



Nelson et al., ApJ, 404, 723, 1993

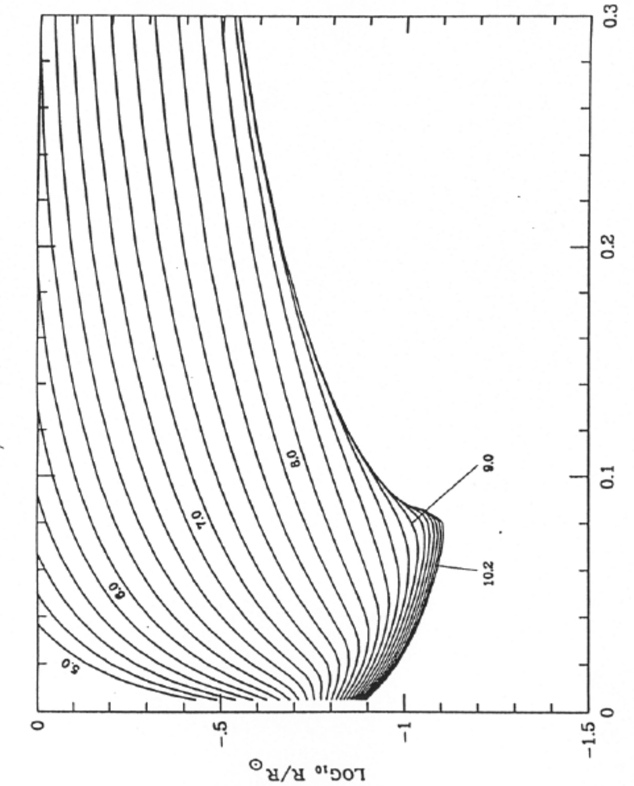
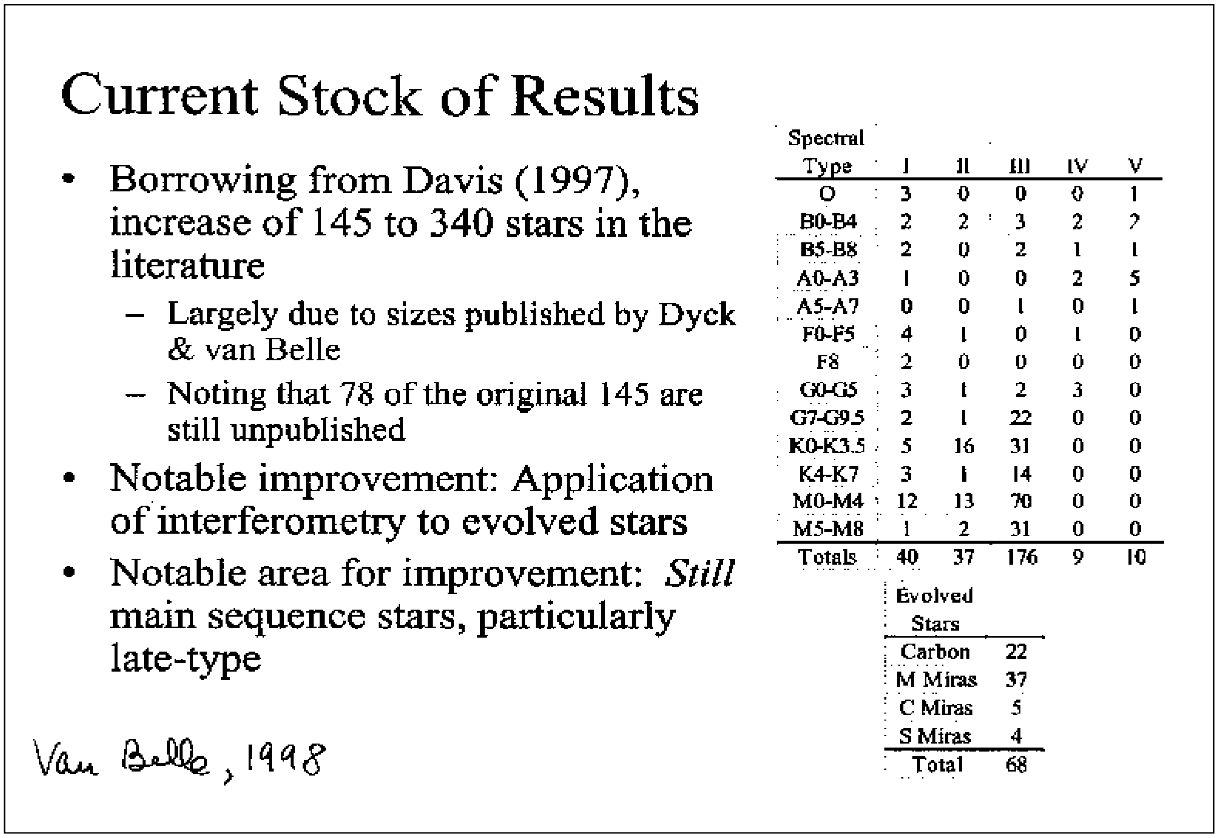


FIG. 4.—Coeval plots of the mass-radius relation for low-mass stars and brown dwarfs. Curves are labeled by the logarithm of the elapsed time (in years) since the start of the evolution; every adjacent pair of curves is separated by a logarithmic time interval of 0.2. Note the inverted mass-radius relation at late times for stars with masses $\lesssim 0.084\ M_\odot$. The effects of deuterium burning (early in the evolution) are omitted for clarity in presentation (see text).



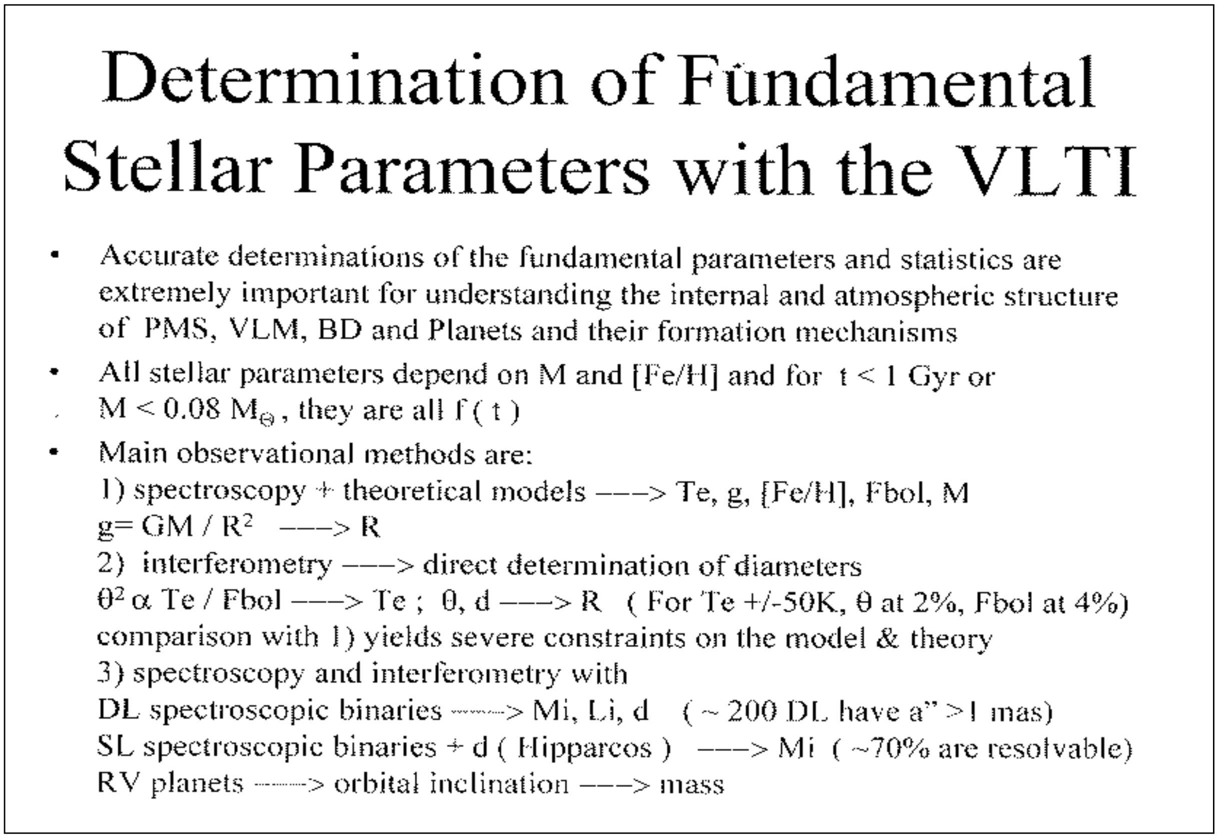
Current Stock of Results

- Borrowing from Davis (1997), increase of 145 to 340 stars in the literature
    - Largely due to sizes published by Dyck & van Belle
    - Noting that 78 of the original 145 are still unpublished
- Notable improvement: Application of interferometry to evolved stars
- Notable area for improvement: *Still* main sequence stars, particularly late-type

Spectral Type	I	II	III	IV	V
O	3	0	0	0	1
B0-B4	2	2	3	2	?
B5-B8	2	0	2	1	1
A0-A3	1	0	0	2	5
A5-A7	0	0	1	0	1
F0-F5	4	1	0	1	0
F8	2	0	0	0	0
G0-G5	3	1	2	3	0
G7-G9.5	2	1	22	0	0
K0-K3.5	5	16	31	0	0
K4-K7	3	1	14	0	0
M0-M4	12	13	70	0	0
M5-M8	1	2	31	0	0
Totals	40	37	176	9	10

Evolved Stars	
Carbon	22
M Miras	37
C Miras	5
S Miras	4
Total	68

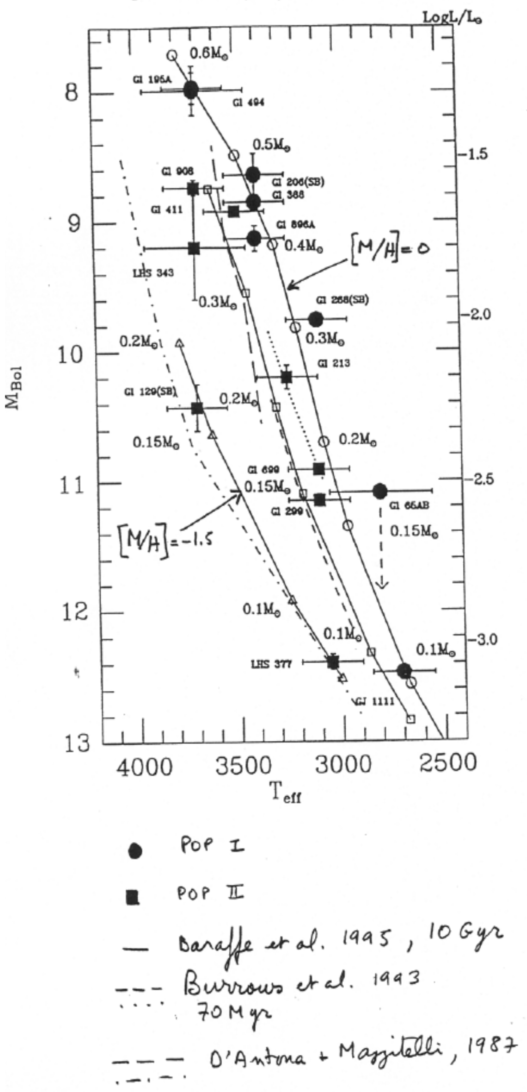
Van Belle, 1998



Determination of Fundamental Stellar Parameters with the VLTI

- Accurate determinations of the fundamental parameters and statistics are extremely important for understanding the internal and atmospheric structure of PMS, VLM, BD and Planets and their formation mechanisms
- All stellar parameters depend on M and [Fe/H] and for t < 1 Gyr or M < 0.08 $M_\odot$, they are all f (t)
- Main observational methods are:
  1) spectroscopy + theoretical models ––-> Te, g, [Fe/H], Fbol, M
  g= GM / R^2 ––-> R
  2) interferometry ––-> direct determination of diameters
  $\theta^2 \alpha$ Te / Fbol ––-> Te ; θ, d ––-> R (For Te +/-50K, θ at 2%, Fbol at 4%)
  comparison with 1) yields severe constraints on the model & theory
  3) spectroscopy and interferometry with
  DL spectroscopic binaries ––-> Mi, Li, d (~ 200 DL have a" >1 mas)
  SL spectroscopic binaries + d (Hipparcos) ––-> Mi (~70% are resolvable)
  RV planets ––-> orbital inclination ––-> mass

Leggett et al., ApJSS, <u>104</u>, 117, 1996



Leggett et al., ApJ, 2000, <u>535</u>, 965

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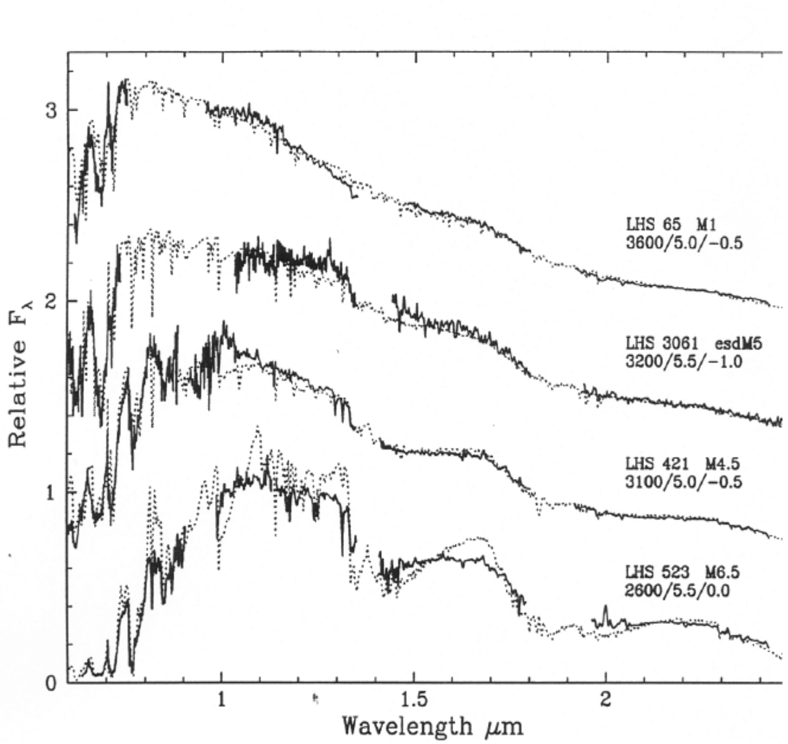


Fig. 9.— Comparison of synthetic (dashed line) and observed (solid line) spectral energy distributions, where the spectra have been normalised to the flux at 1.2μm and offset. The best fit model parameters $\underline{T_{eff}/\log g/[m/H]}$ are given for each star.

$$g = \frac{GM}{R^2}$$

$$d, g, \bullet, F_{BOL} \rightarrow (R, M)_{sp}$$

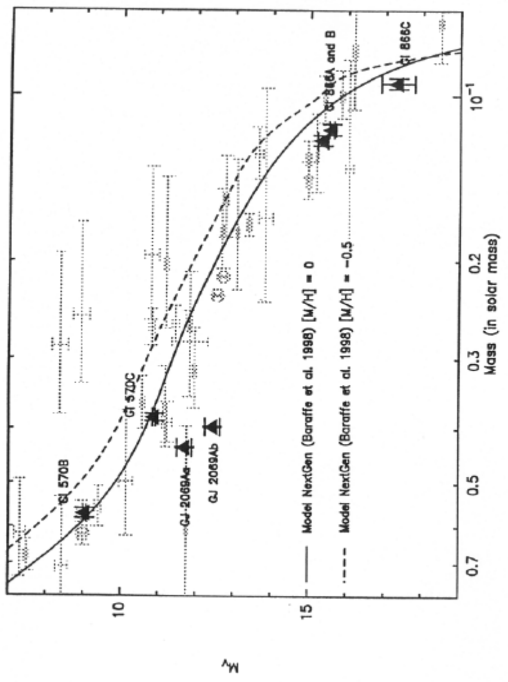
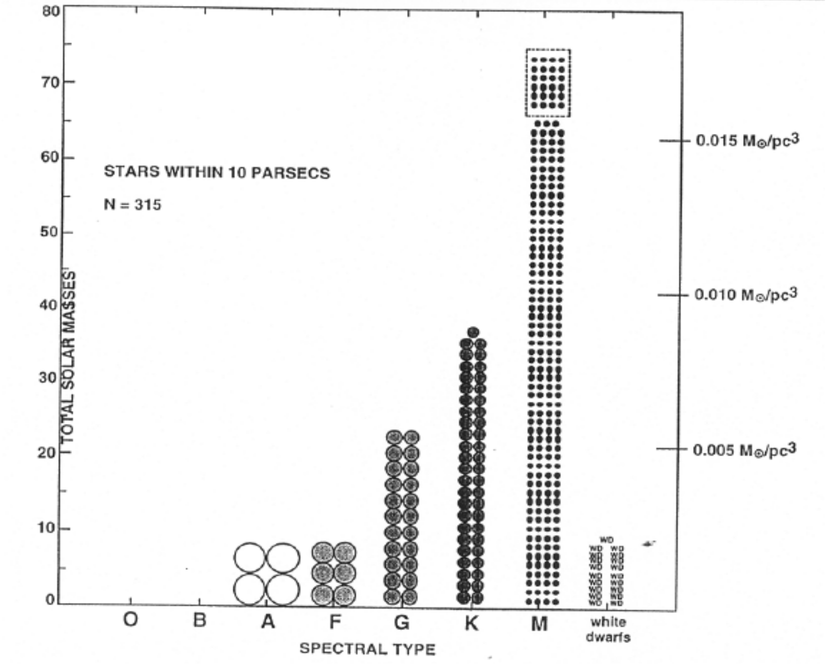
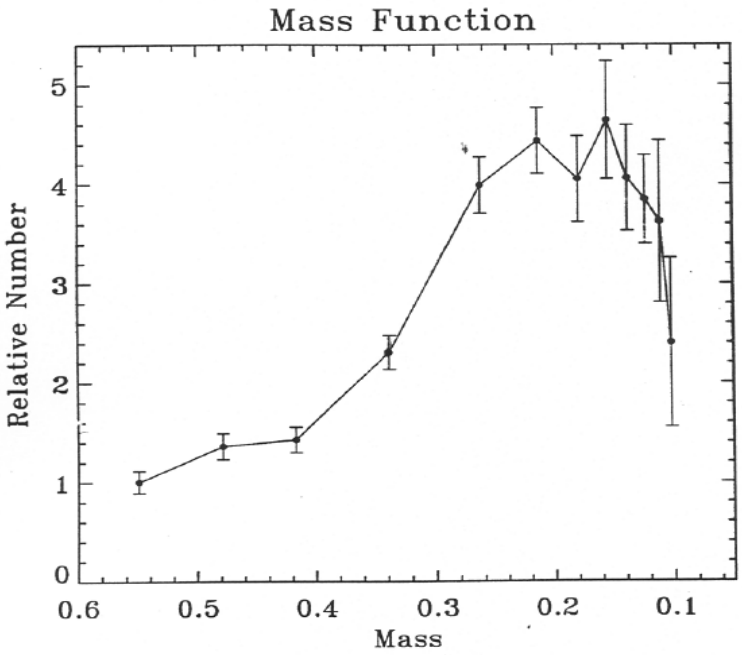


Fig. 4. V band mass-luminosity relation. The error bars without points are data from Henry and McCarthy (1993), Henry et al. (1999) and Torres et al. (1999). The circles represent the two well known M eclipsing binaries, YY Gem and CM Dra. The triangles represent our recent mesurements: GJ 2069A, Gl 570B and the three components of Gl 866. The two curves are 5 Gyr theoretical isochrones Baraffe et al. (1998) for two metallicities.

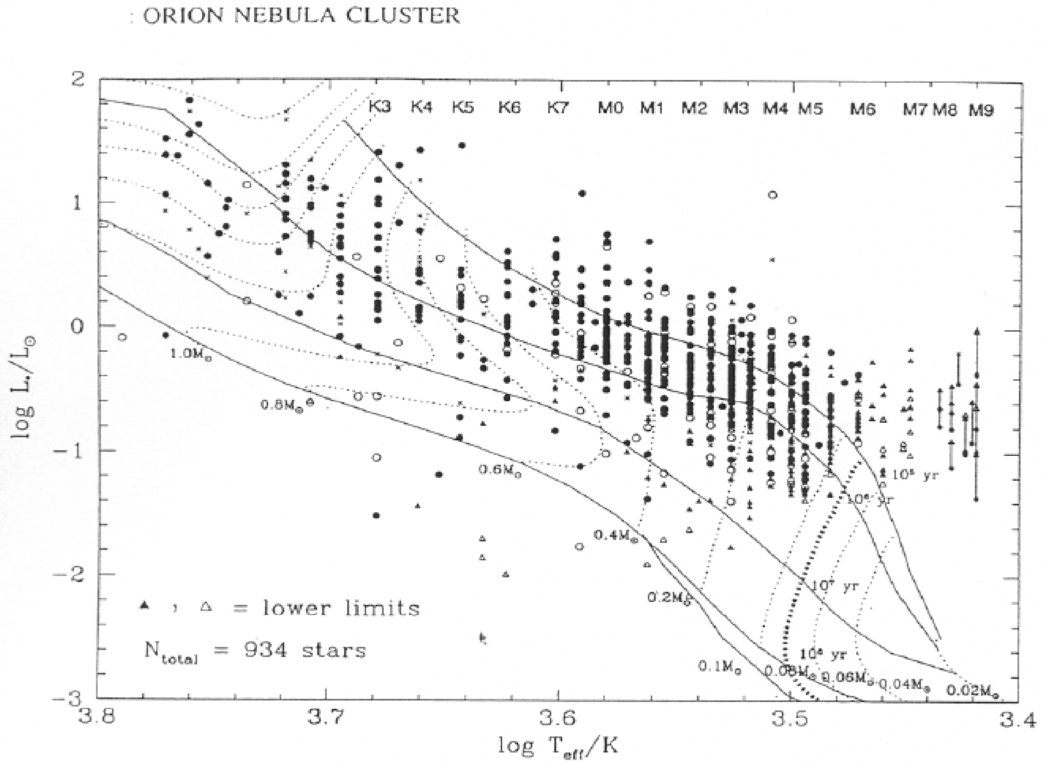
Delfosse et al., 1999, A+A, 350, 39

1000 Stars (cont'd)





NGC 6397
Paresce et al., 1995, ApJ, 440, 216



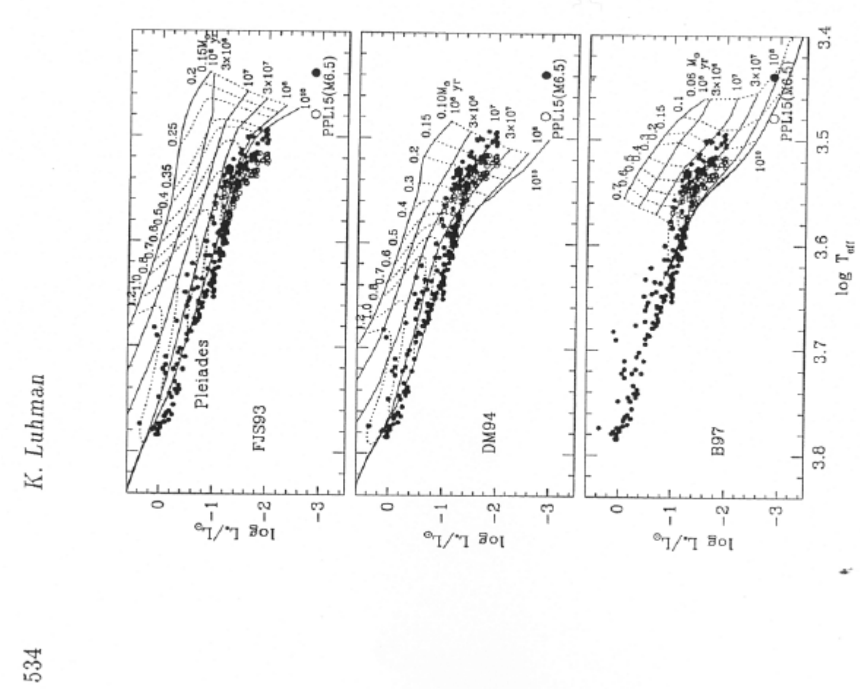
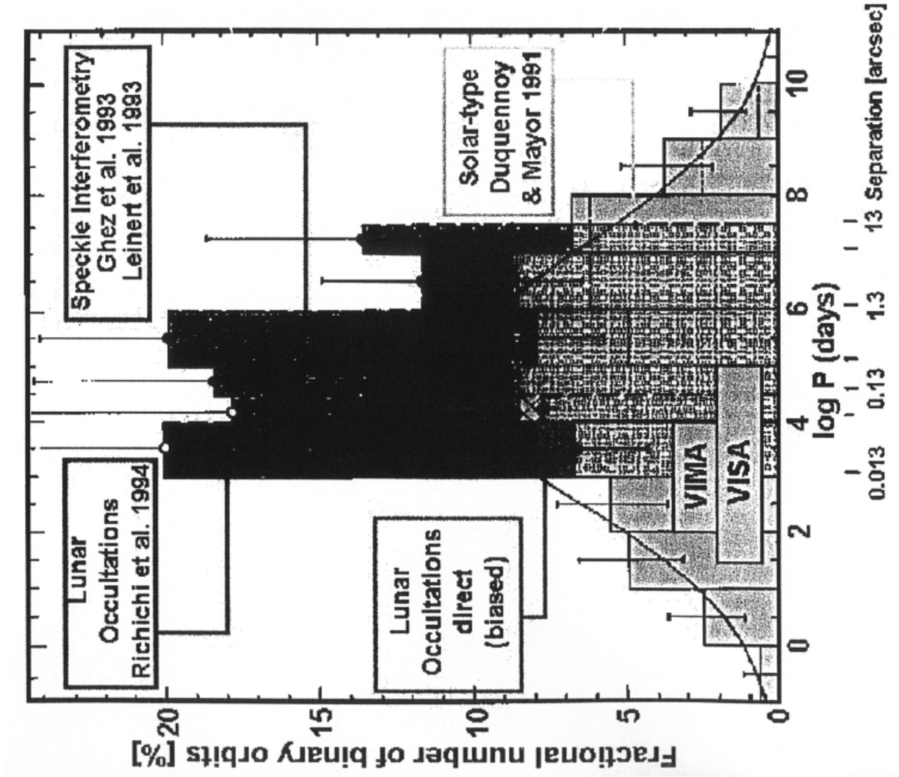
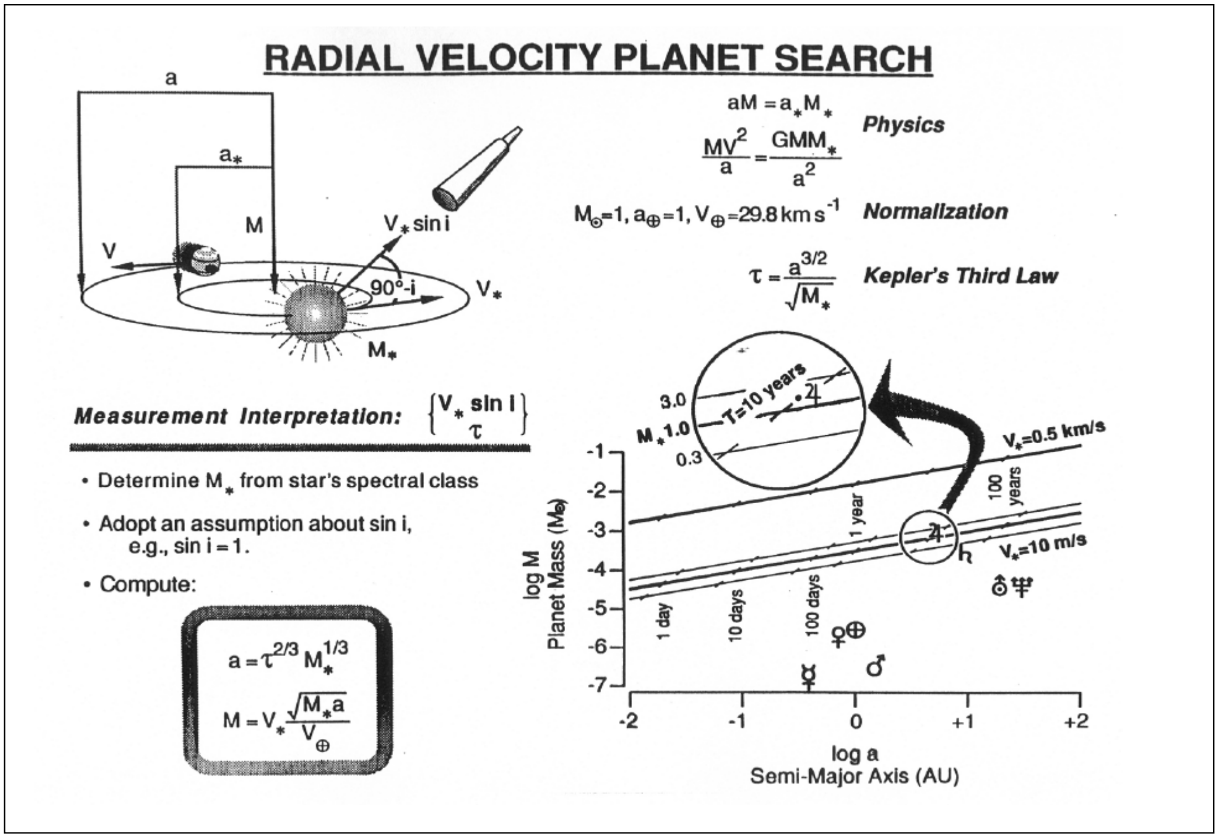


Figure 2. The Pleiades with evolutionary tracks of FJS93, DM94, and BCAH97. Solid and open circles were transformed with the Leggett et. al. (1996) and Kirkpatrick et al. (1993) temperature scales, respectively.





RADIAL VELOCITY PLANET SEARCH

$aM = a_* M_*$ ***Physics***

$\frac{MV^2}{a} = \frac{GMM_*}{a^2}$

$M_\odot=1, a_\oplus=1, V_\oplus=29.8\,\mathrm{km\,s^{-1}}$ ***Normalization***

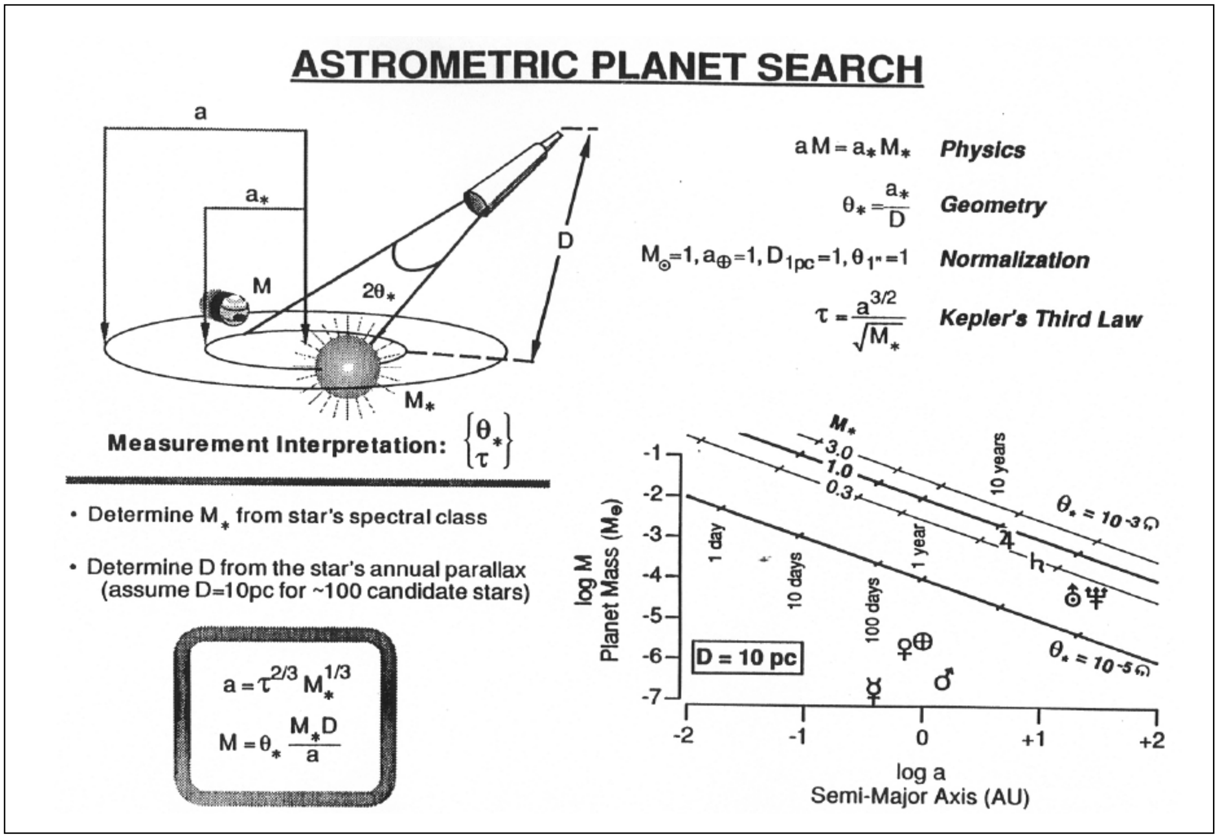
$\tau = \frac{a^{3/2}}{\sqrt{M_*}}$ ***Kepler's Third Law***

Measurement Interpretation: $\begin{Bmatrix} V_* \sin i \\ \tau \end{Bmatrix}$

- Determine M_* from star's spectral class
- Adopt an assumption about sin i, e.g., sin i = 1.
- Compute:

$$a = \tau^{2/3} M_*^{1/3}$$

$$M = V_* \frac{\sqrt{M_* a}}{V_\oplus}$$



ASTROMETRIC PLANET SEARCH

$aM = a_* M_*$ ***Physics***

$\theta_* = \frac{a_*}{D}$ ***Geometry***

$M_\odot=1, a_\oplus=1, D_{1pc}=1, \theta_{1''}=1$ ***Normalization***

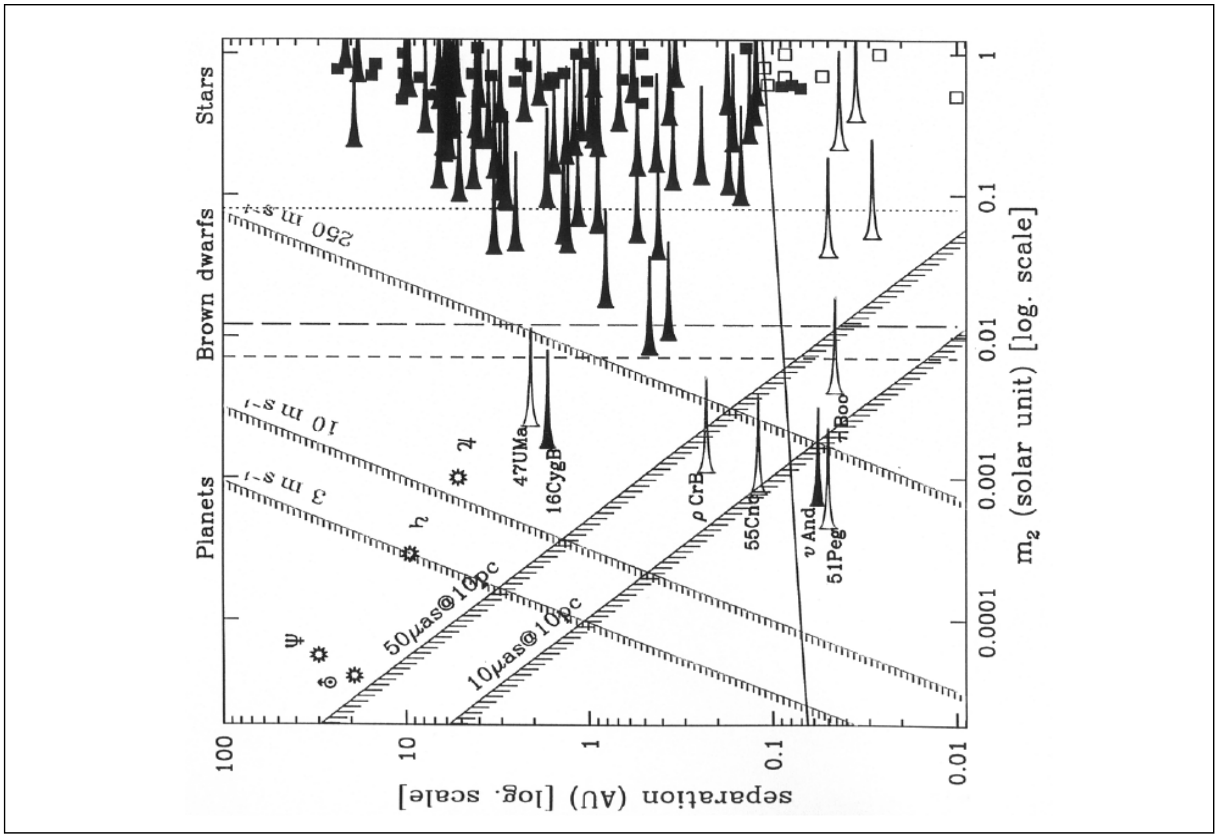
$\tau = \frac{a^{3/2}}{\sqrt{M_*}}$ ***Kepler's Third Law***

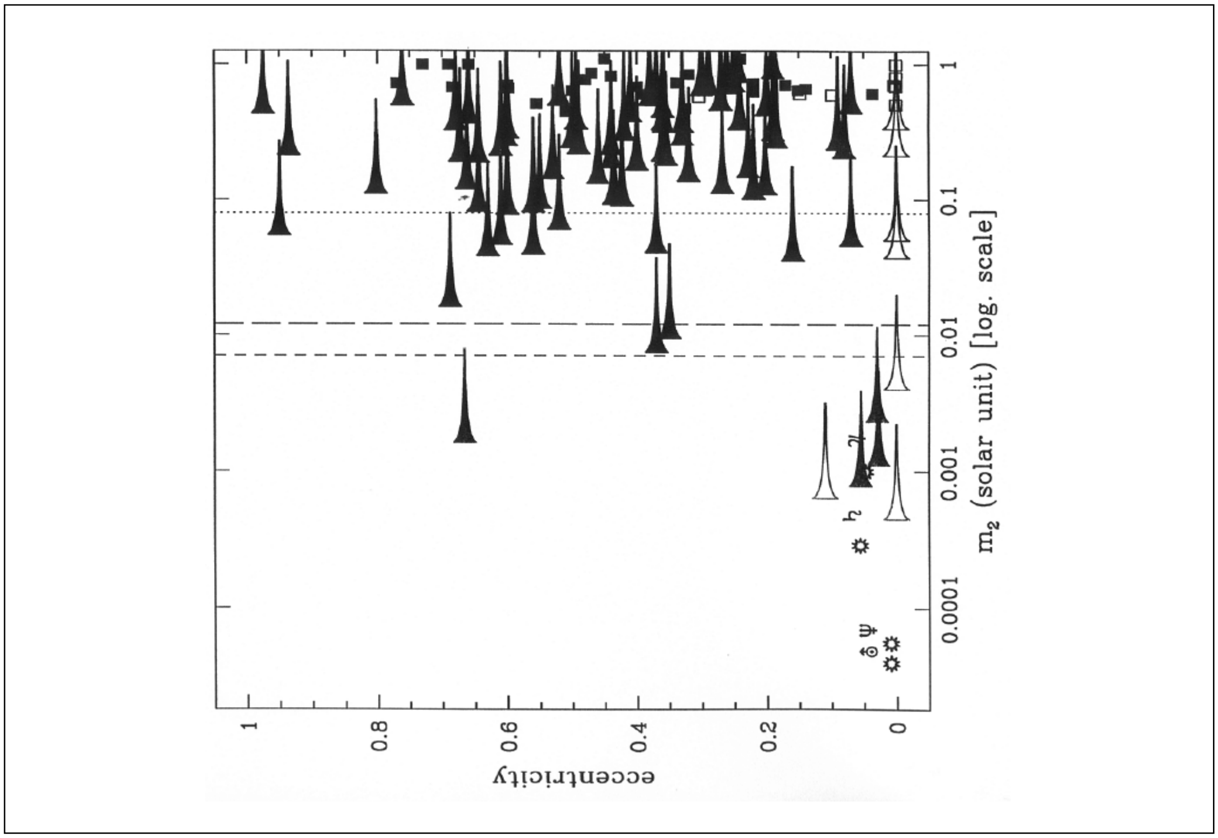
Measurement Interpretation: $\begin{Bmatrix} \theta_* \\ \tau \end{Bmatrix}$

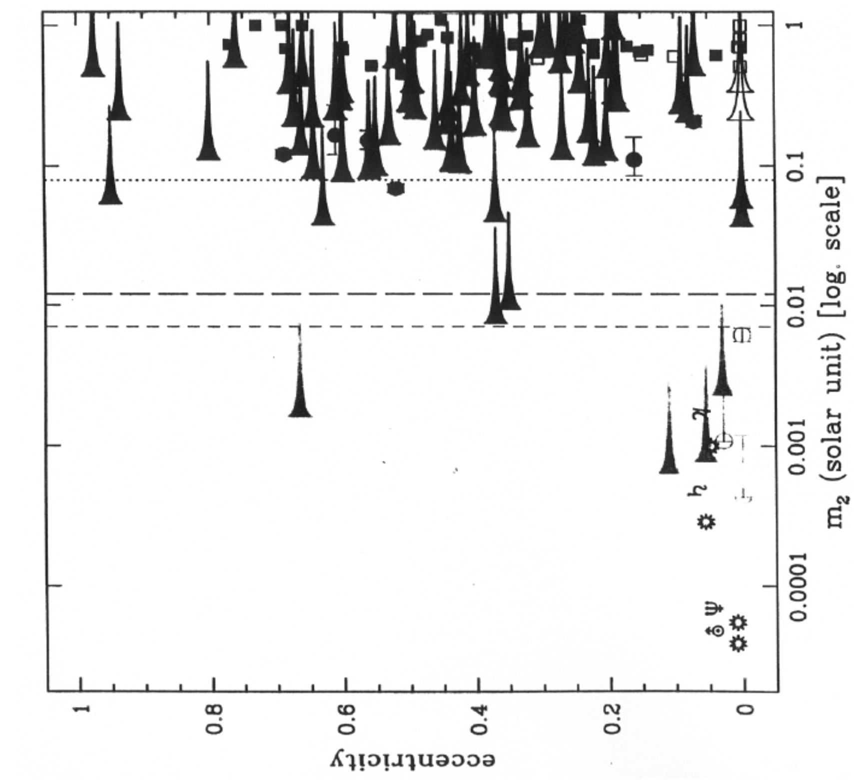
- Determine M_* from star's spectral class
- Determine D from the star's annual parallax (assume D=10pc for ~100 candidate stars)

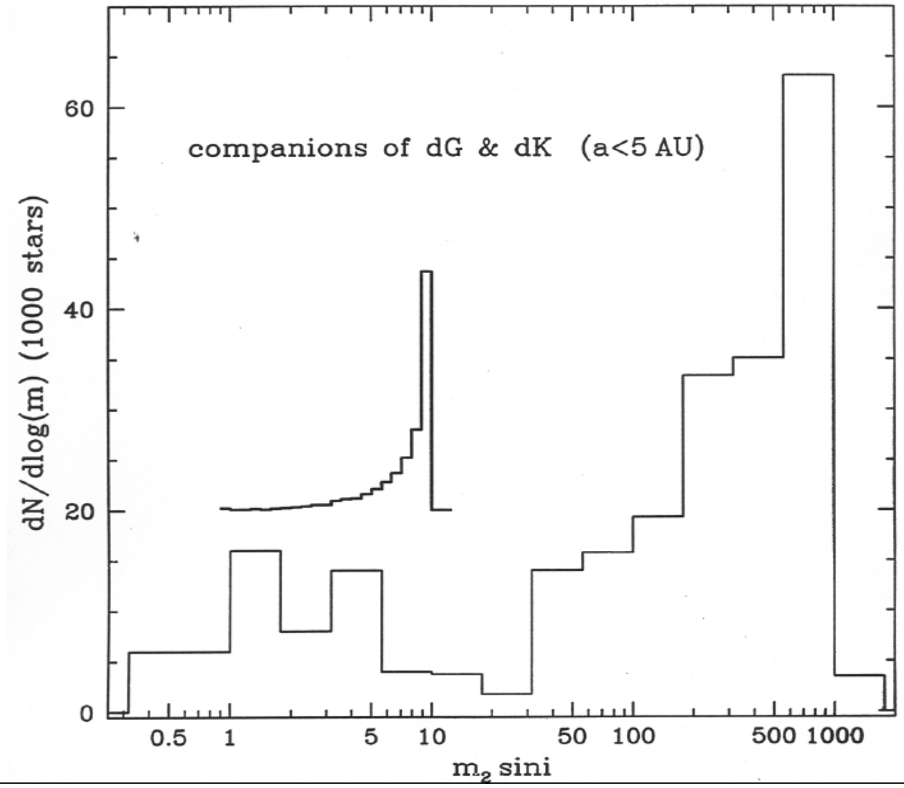
$$a = \tau^{2/3} M_*^{1/3}$$

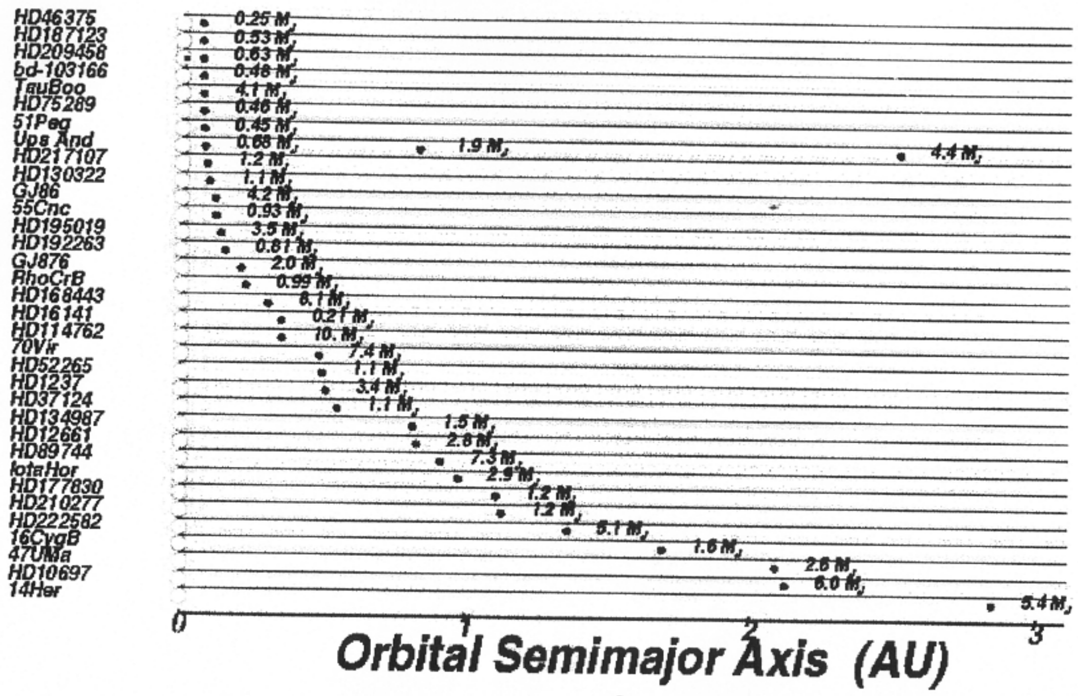
$$M = \theta_* \frac{M_* D}{a}$$


Planets
Brown dwarfs
Stars
3 m s⁻¹
10 m s⁻¹
250 m s⁻¹
50μas@10pc
10μas@10pc
♆
♅
♄
♃
47UMa
16CygB
ρ CrB
55Cnc
υ And
51Peg
τ Boo
separation (AU) [log. scale]
100
10
1
0.1
0.01
m₂ (solar unit) [log. scale]
0.0001
0.001
0.01
0.1
1

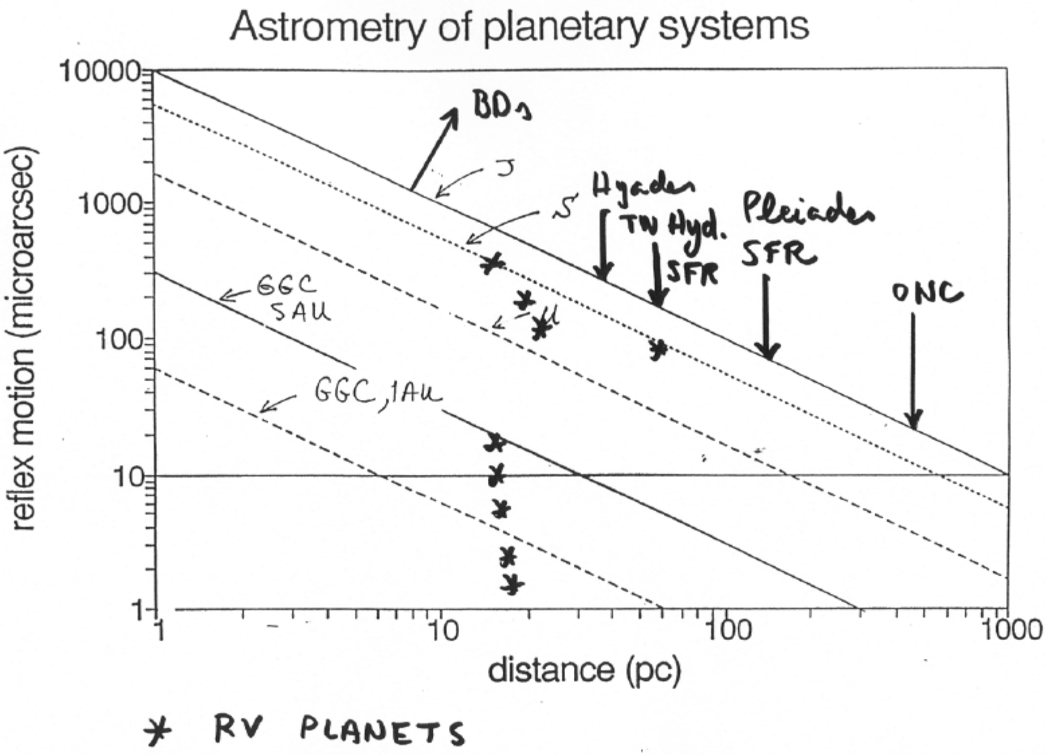

eccentricity
1
0.8
0.6
0.4
0.2
0
♆
♅
♄
♃
m₂ (solar unit) [log. scale]
0.0001
0.001
0.01
0.1
1

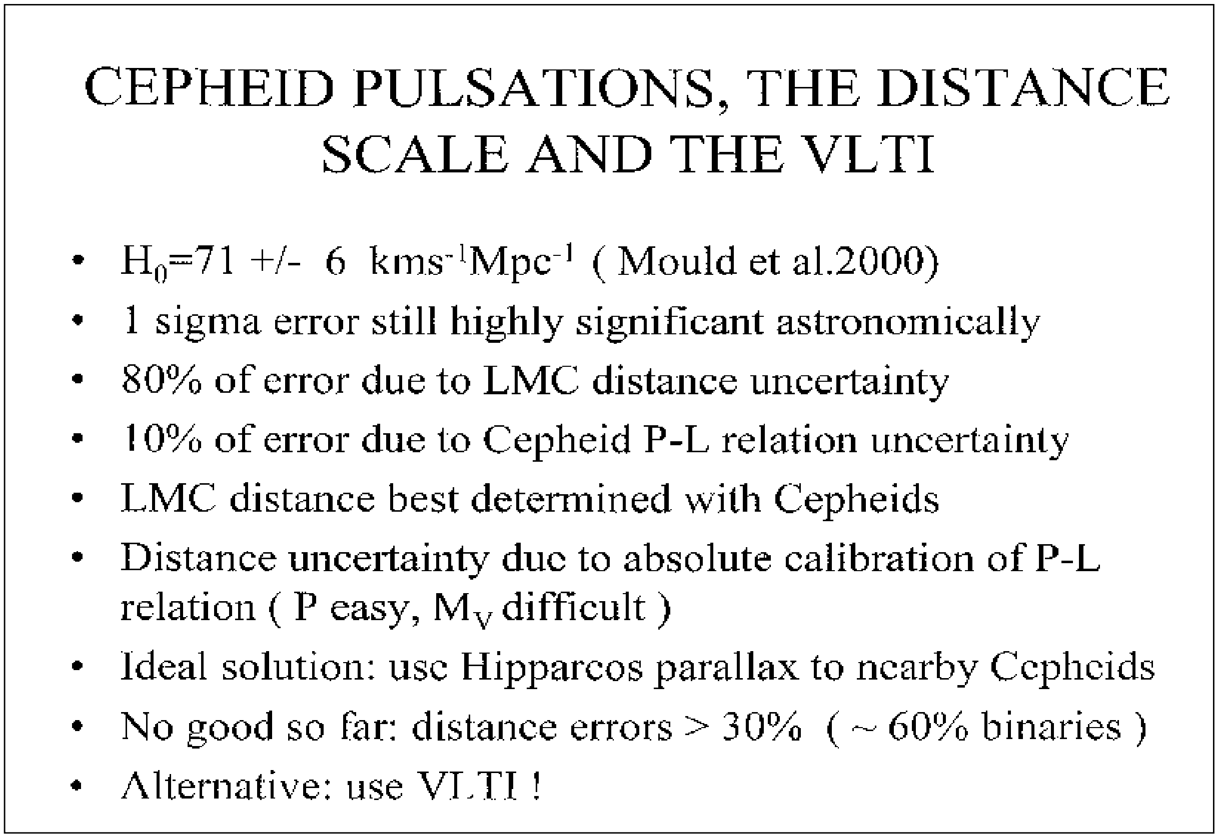

eccentricity
0
0.2
0.4
0.6
0.8
1
m$_2$ (solar unit) [log. scale]
0.0001
0.001
0.01
0.1
1


companions of dG & dK (a<5 AU)
dN/dlog(m) (1000 stars)
0
20
40
60
0.5
1
5
10
50
100
500
1000
m$_2$ sini



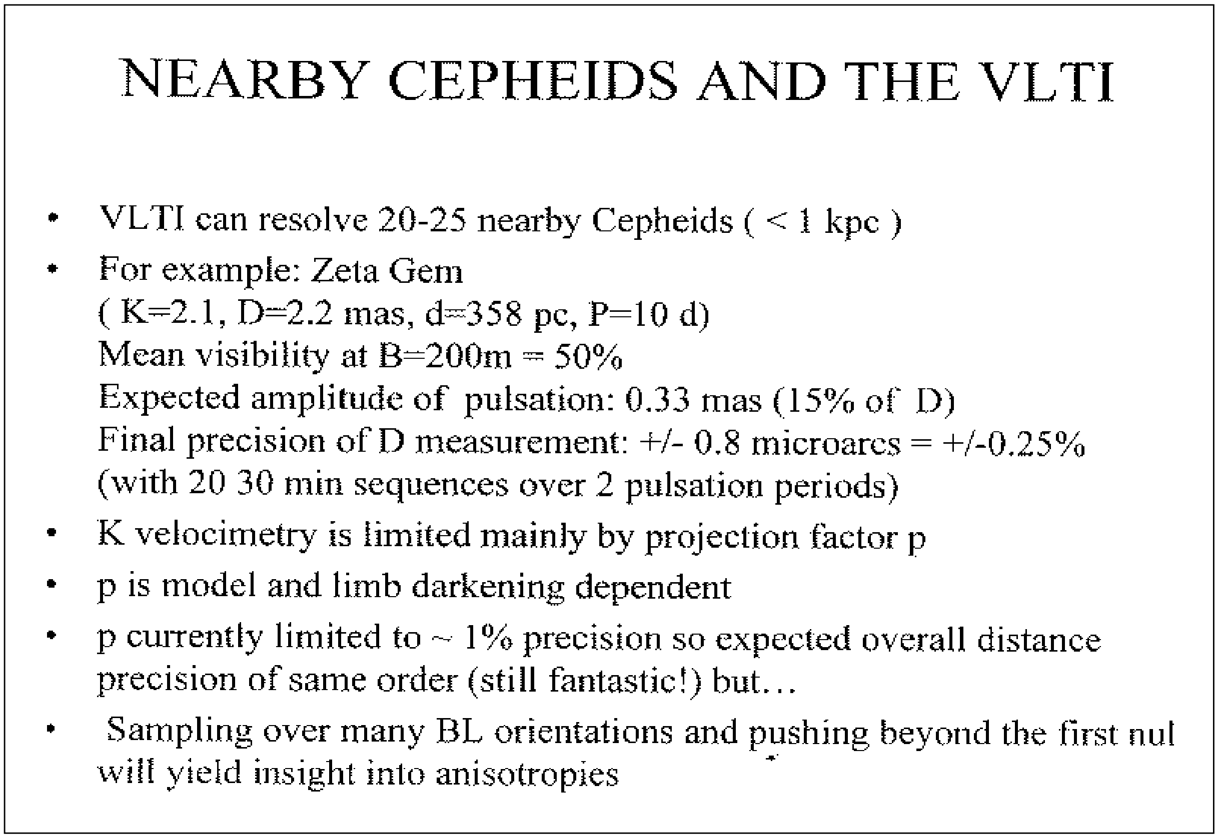
→||← VLTI RESOLUTION AT d = 20 pc = 0.05 AU





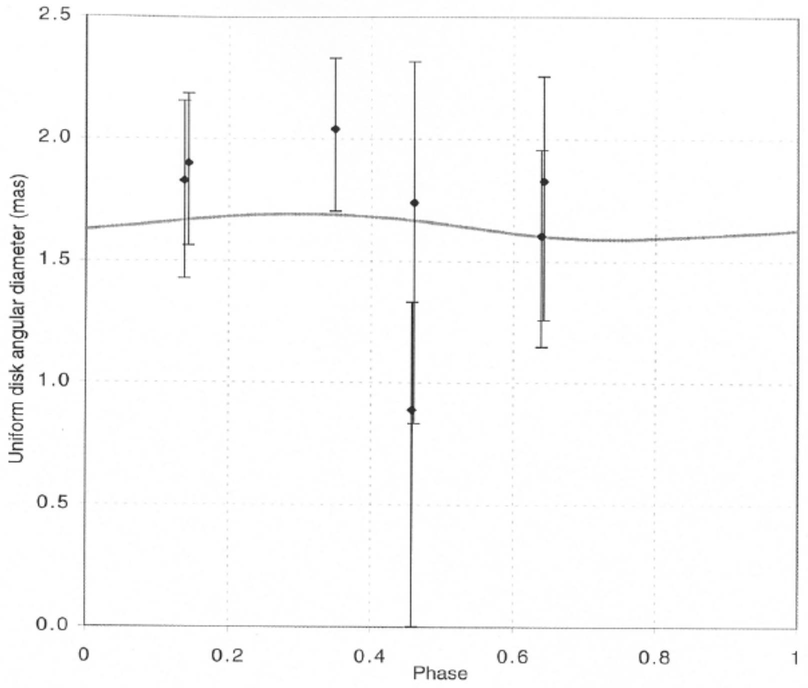
CEPHEID PULSATIONS, THE DISTANCE SCALE AND THE VLTI

- H_0=71 +/- 6 kms^{-1}Mpc^{-1} (Mould et al.2000)
- 1 sigma error still highly significant astronomically
- 80% of error due to LMC distance uncertainty
- 10% of error due to Cepheid P-L relation uncertainty
- LMC distance best determined with Cepheids
- Distance uncertainty due to absolute calibration of P-L relation (P easy, M_V difficult)
- Ideal solution: use Hipparcos parallax to nearby Cepheids
- No good so far: distance errors > 30% (~ 60% binaries)
- Alternative: use VLTI !



NEARBY CEPHEIDS AND THE VLTI

- VLTI can resolve 20-25 nearby Cepheids (< 1 kpc)
- For example: Zeta Gem
  (K=2.1, D=2.2 mas, d=358 pc, P=10 d)
  Mean visibility at B=200m = 50%
  Expected amplitude of pulsation: 0.33 mas (15% of D)
  Final precision of D measurement: +/- 0.8 microarcs = +/-0.25%
  (with 20 30 min sequences over 2 pulsation periods)
- K velocimetry is limited mainly by projection factor p
- p is model and limb darkening dependent
- p currently limited to ~ 1% precision so expected overall distance precision of same order (still fantastic!) but…
- Sampling over many BL orientations and pushing beyond the first nul will yield insight into anisotropies



Kervella et al., 2000, A&A, in press