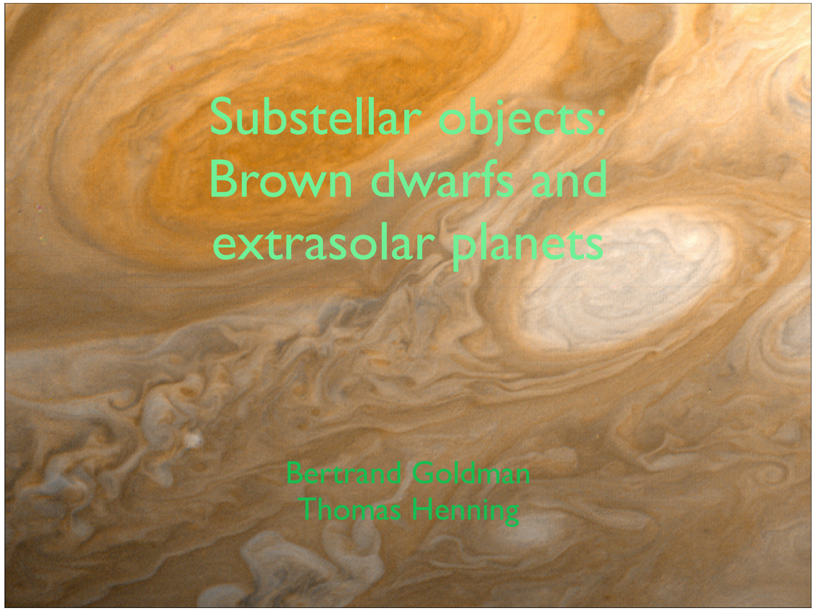


1

2

Current schedule

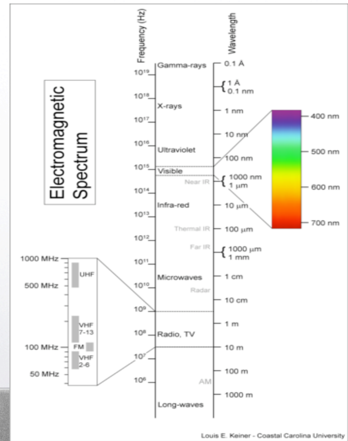
- Lecturer might change
- Topic distribution might change– suggestions welcomed

	Date		Title
BG	17.10.06		Organisation, introduction
BG	24.10.06	BD	Spectral classification
BG	31.10.06	BD	Observational properties of brown dwarfs
BG	7.11.06	BD	Structure and evolution
TH	14.11.06	BD	How to search for brown dwarfs: in the field, in star forming regions, as companions to stars and brown dwarfs, and using microlensing effect
BG	21.11.06	BD	How many brow dwarfs in the Galaxy: Initial mass function. Do the BD contribute to the Dark Matter?
BG	28.11.06	BD	Formation: Do brown dwarfs form like stars or like planets?
BG	5.12.06	BD	Brown dwarfs in their infancy
BG	12.12.06	BD	The future of brown dwarf studies
TH	19.12.06	EP	introduction, history
TH	9.01.07	EP	How do we find searches extrasolar planets: the transit, microlensing, astrometry, direct detection methods
TH	16.01.07	EP	Results of the Radial Velocity measurements. Statistics and comparison of the methods.
TH	23.01.07	EP	Formation of (extrasolar) planets
BG	30.01.07	EP	Atmospheres of extrasolar planets
BG	6.02.07		Conclusions, prospects

3

Scales and units: wavelengths

The electromagnetic spectrum



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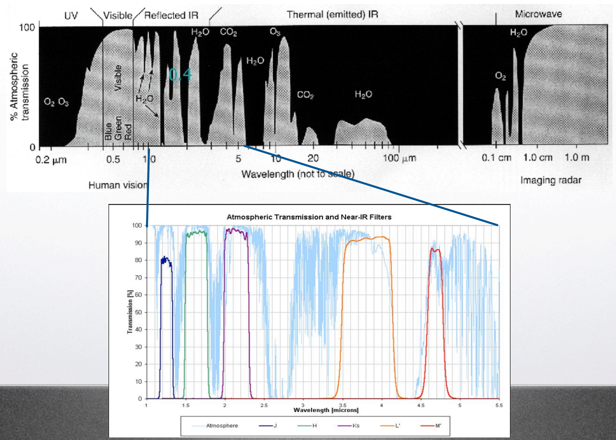
Filters



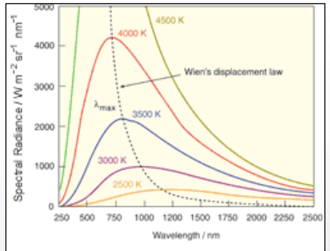
Colours

The Planck radiation law (1900):

$$F_\lambda = \frac{2\pi h c^2}{\lambda^5 \left(e^{\frac{hc}{\lambda k T}} - 1\right)}$$

=> Stefan's law: $L = 4\pi R_{BD}^2 . \sigma . T_{eff}^4$

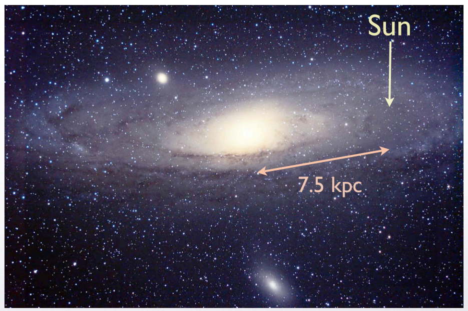
and Wien's law: $\lambda_{max} = \frac{2.99\text{mm}}{T}$



Black body radiation according to Planck's Law

Scales and units: distance

- Most observed BDs and exoplanets: within 100 pc *really locally*
- Some exceptions: transit and microlensing detections (object not [yet] imaged)



M31 Andromeda

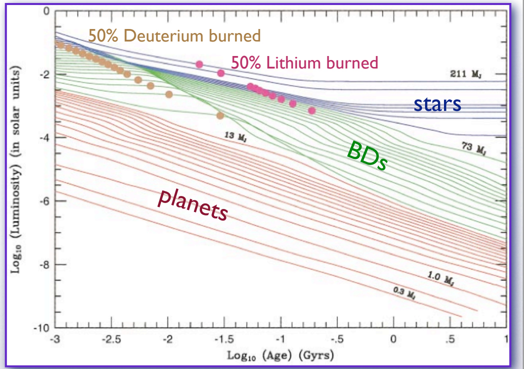
Other useful scales

- Stellar space velocities (with respect to the Sun):
  - thin disk: 30 km/s *(typical)*
  - thick disk: 80 km/s
  - stellar halo/spheroid: 200 km/s
  - proper motion: angular velocity: $\mu(\text{arcsec / yr}) \approx \frac{v_\perp(\text{km / s})}{5.d(\text{pc})}$
- Angular positional accuracy:
  - absolute: 0.1" for CCD-based catalogues, worst for plates
  - relative: 1–10 milliarcseconds
  - parallax: $\pi(\text{arcsec}) \equiv \frac{1}{d(\text{pc})}$
- Masses:
  - Sun/Jupiter: 1 $M_\odot$=1047 $M_{♃}$
  - Jupiter/Earth: 1 $M_{♃}$= 318 $M_\oplus$
  - Saturn/Earth: 1 $M_{♄}$= 95 $M_\oplus$

Definition of brown dwarfs

- Main parameter: mass
  - slightly function of metallicity
- Criteria:
  - *stable* H burning
  - ${}^2_1H = De$ burning

Luminosity



Age

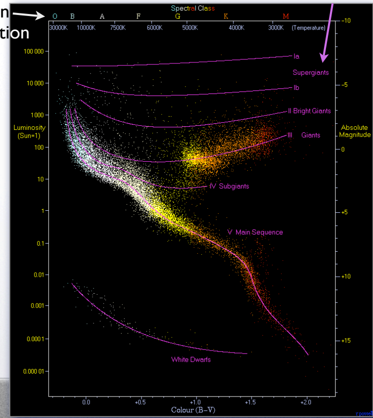
Burrows, 2001

Hertzprung-Russell diagram

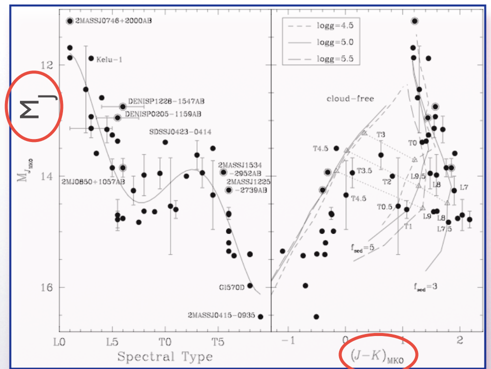
Morgan-Keenan spectral classification

Yerkes MKK (luminosity) classification

- proposed in 1910
- 22,000 nearby stars with Hipparcos parallaxes and Gliese stars.



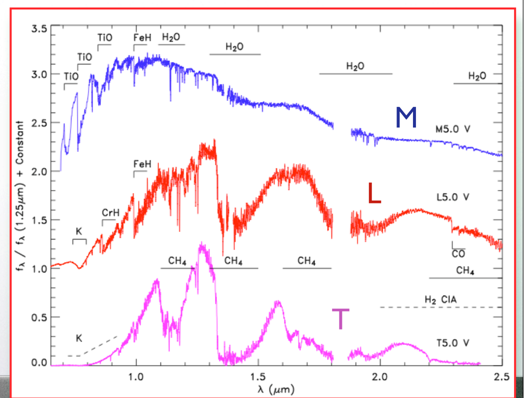
Brown dwarf colour-magnitude diagram



Golimowski, Cool Stars 13, 2005
models by Ackerman & Marley, 2001

Stellar classification

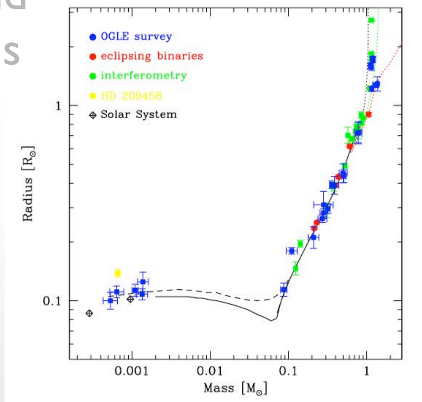
- Two new spectral classes
- Specific species:
  - Ms: TiO
  - Ls: dust, FeH, H_2O
  - Ts: methane, H_2O



Cushing, Cool Stars #13, 2005

Brown dwarf and exoplanet radius

Degenerate electron gas of cooler cores prevents further contraction



Detection of brown dwarfs

- Unusual colours
  - model predicted
  - contamination by warmer stars and galaxies
- Companions of nearby stars
  - requires high contrast ratio with high angular resolution
- High proper motions objects
  - incomplete, bias towards older populations
  - requires some patience and twice telescope time
- Late type objects in young clusters
  - known types, but lower gravity
  - contamination by field stars

A very recent field

First young brown dwarf in the Pleiades (1995)

LETTERS TO NATURE

Discovery of a brown dwarf in the Pleiades star cluster

R. Rebolo, M. R. Zapatero Osorio & E. L. Martín

Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain

Brown dwarfs are cool star-like objects that have insufficient mass to maintain stable nuclear fusion in their interiors. Although brown dwarfs are not stars, they are expected to form in the same way, and their frequency of occurrence should reflect the trends seen in the birthrates of low-mass stars. But finding brown dwarfs has proved to be difficult, because of their low intrinsic luminosity. The nearby Pleiades star cluster is widely recognized as a likely host for detectable brown dwarfs because of its young age—the still-contracting brown dwarfs should radiate a large fraction of their gravitational energy at near-infrared wavelengths. Here we report the discovery of a brown dwarf near the centre of the Pleiades. The luminosity and temperature of this object are so low that its mass must be less than 0.08 solar masses, the accepted lower limit on the mass of a true star[1–3]. The detection of only one brown dwarf within our survey area is consistent with a smooth extrapolation of the stellar mass function of the Pleiades[4], suggesting that brown dwarfs, although probably quite numerous in the Galactic disk, are unlikely to comprise more than ~1% of its mass.

Only about half a dozen extremely cool dwarfs with spectral types M9 or later have been identified[5]. At present they are the best candidates for brown dwarfs. Their mass-luminosity and mass-spectral-type relationships[6,7] show that these objects are indeed very close to the substellar limit, but uncertainties in

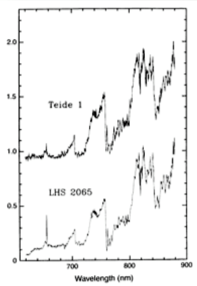


FIG. 1 The optical spectrum of Teide 1 (upper trace) and of the M9 dwarf LHS 2065 (lower trace). The flux scale of both spectra is normalized to unity at 825 nm. An offset has been added to the spectrum of Teide 1 for clarity.

First (cool) brown dwarf

Gl 229B (1995) companion to Gl 229A, a M1/M2 dwarf at 5.8 pc

LETTERS TO NATURE

Discovery of a cool brown dwarf

T. Nakajima*, B. R. Oppenheimer*, S. R. Kulkarni*, D. A. Golimowski†, K. Matthews* & S. T. Durrance†

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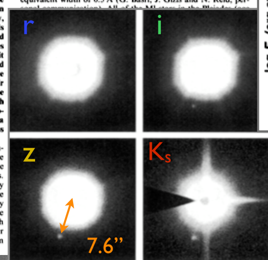
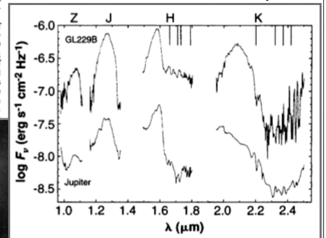
† Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, Maryland 21218, USA

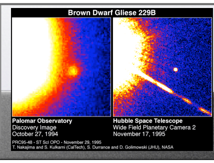
Brown dwarfs are star-like objects with masses less than 0.08 times that of the Sun, which are unable to sustain hydrogen fusion in their interiors[1–4]. They are very hard to detect, as most of the energy of gravitational contraction is radiated away within ~10^8 yr, leaving only a very low residual luminosity. Accordingly, almost all searches for brown dwarfs have been directed towards clusters of young stars—a strategy that has recently proved successful[5,6]. But there are only modest observable differences between young brown dwarfs and very low-mass stars, making it difficult to identify the former without appealing to sophisticated models[7]. Older brown dwarfs should have a more distinctive appearance, and if they are companions to nearby stars, their luminosity can be determined unambiguously. Here we report the discovery of a probable companion to the nearby star Gl229, with no more than one-tenth the luminosity of the least luminous hydrogen-burning star. We conclude that the companion, Gl229B, is a brown dwarf with a temperature of less than 1,200 K, and a mass ~20–50 times that of Jupiter.

Three years ago, we initiated a search[8] for brown-dwarf companions to stars less than 15 pc away. With this strategy, we utilize the precisely known distances to these stars to determine accurately the total luminosity of any discovered companions. In all models of low-mass stars[4], the lowest luminosity of any hydrogen-burning star is $L_{min} \gtrsim 10^{-4} L_\odot$. Brown dwarfs of age 10^9 yr have luminosities well below L_{min} and are therefore clearly distinguishable[3] from low-mass stars. Consequently, we have begun the 'Palomar-Byr' survey, a survey of all nearby stars with ages of about one billion (10^9) years. These stars have either small space motion[9] or have active coronae (as inferred from copious Hα[10] or X-ray emission[11]), both of which are indicators of stellar youth. The survey consists of both optical coronagraphic imaging and infrared direct imaging of the stars.

During the past year, we have observed about 100 stars of this sample. Preliminary analysis of the data revealed a very intriguing proper-motion companion to the nearby star, Gl229 (also known as HD42581 and LHS1827; spectral type MIV; $M_V = 9.3$, parallax[9] 0.1749 ± 0.0045 arcsec or a distance of 5.7 pc; see ref. 12 for further details). This star was selected from a list of stars with known low space motion[9]. Based on its kinematics it has been classified as a 'young' disk star, age ~10^9 yr. However, the star exhibits Hα absorption with an equivalent width of 0.5 Å (G. Basri, J. Gizis and N. Reid, per-





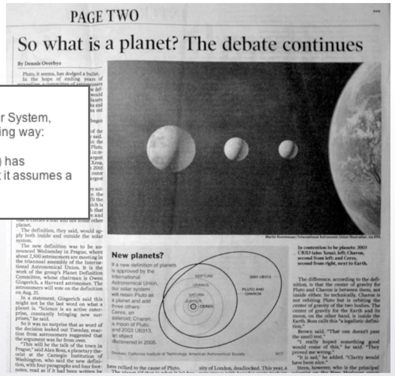


Definition of "planet"

- Solar system: cf. IAU in Prag:

RESOLUTION 5A
The IAU therefore resolves that "planets" and other bodies in our Solar System, except satellites, be defined into three distinct categories in the following way:

(1) A "planet"[1] is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit.

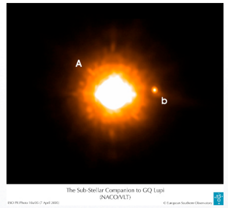


- Extrasolar planets: various options:
  - formation?
  - association (with a host star)
  - mass (not burning De): <13 $M_{Jupiter}$

Int'l Herald Trib. 17/08/06

Detection of extrasolar planets

- Imaging: direct detection
  - => 1–4?
- Movements of the host star
  - pulsar (1992,1994)
- Acceleration of the host star
  - 198 (1995…)
- Occultation of the host star
  - 14 (2004…)
- Gravitational lensing (microlensing) of a background star
  - 4 (2004…)



Wobbling of the host star

- Time-delay: milli-second pulsars
- Astrometry:
  - Ground based projects: VLT, Keck, LBT
  - Long-term space projects:
    - GAIA
    - TPF-I, Darwin

Aerial View of Paranal Observing Platform with VLTI Light Paths

ESO PR Photo 10f/01 (18 March 2001) © European Southern Observatory

First extrasolar planet

(around a pulsar)

A planetary system around the millisecond pulsar PSR1257+12

A. Wolszczan* & D. A. Frail†

* National Astronomy and Ionosphere Center, Arecibo Observatory, Arecibo, Puerto Rico 00613, USA
† National Radio Astronomy Observatory, Socorro, New Mexico 87801, USA

MILLISECOND radio pulsars, which are old (~10^9 yr), rapidly rotating neutron stars believed to be spun up by accretion of matter from their stellar companions, are usually found in binary systems with other degenerate stars[1]. Using the 305-m Arecibo radiotelescope to make precise timing measurements of pulses from the recently discovered 6.2-ms pulsar PSR1257+12 (ref. 2), we demonstrate that, rather than being associated with a stellar object, the pulsar is orbited by two or more planet-sized bodies. The planets detected so far have masses of at least 2.8 $M_\oplus$ and 3.4 $M_\oplus$, where $M_\oplus$ is the mass of the Earth. Their respective distances from the pulsar are 0.47 AU and 0.36 AU, and they move in almost circular orbits with periods of 98.2 and 66.6 days. Observations indicate that at least one more planet may be present in this system. The detection of a planetary system around a nearby (~500 pc), old neutron star, together with the recent report on a planetary companion to the pulsar PSR1829−10 (ref. 3) raises the tantalizing possibility that a non-negligible fraction of neutron stars observable as radio pulsars may be orbited by planet-like bodies.

The 6.2-ms pulsar PSR1257+12 (Fig. 1) was discovered during the search at high galactic latitudes for millisecond pulsars conducted in February 1990 with the 305-m Arecibo radiotelescope at a frequency of 430 MHz (ref. 2). The characteristics of this survey and the details of data analysis are described else-

one as a post-fit residual, implying that the pulse arrival times of PSR1257+12 are indeed … odicities. Further detaile… periodicities are independe… millisecond pulsars routinel… data acquisition equipment… residuals.

Millisecond pulsars are e… timing observations of obje… (ref. 6) have not revealed a… variations or 'glitches' at the… of younger pulsars and bel… seismology[7]. The frequency…

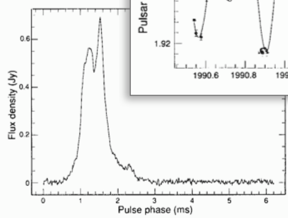
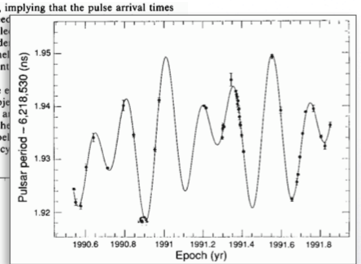


FIG. 1. The average pulse profile of PSR1257+12 at 430 MHz. The effective time resolution is ~12 µs.

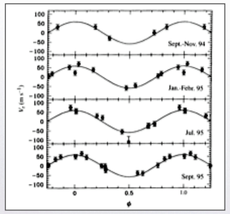


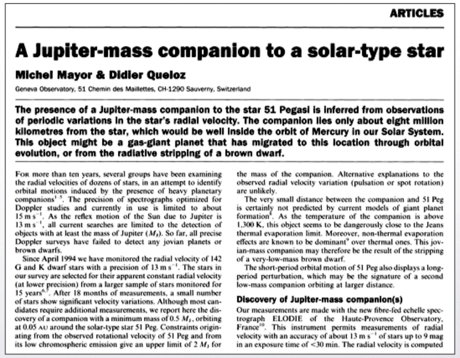
First extrasolar planet

around a main-sequence (variable) star

51 Pegasi B, 1995

561 papers




ARTICLES

A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

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The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

For more than ten years, several groups have been examining the radial velocities of dozens of stars, in an attempt to identify orbital motions induced by the presence of heavy planetary companions[1-5]. The precision of spectrographs optimized for Doppler studies and currently in use is limited to about 15 m s^{-1}. As the reflex motion of the Sun due to Jupiter is 13 m s^{-1}, all current searches are limited to the detection of objects with at least the mass of Jupiter (M_J). So far, all precise Doppler surveys have failed to detect any jovian planets or brown dwarfs.

Since April 1994 we have monitored the radial velocity of 142 G and K dwarf stars with a precision of 13 m s^{-1}. The stars in our survey are selected for their apparent constant radial velocity (at lower precision) from a larger sample of stars monitored for 15 years[6,7]. After 18 months of measurements, a small number of stars show significant velocity variations. Although most candidates require additional measurements, we report here the discovery of a companion with a minimum mass of 0.5 M_J, orbiting at 0.05 AU around the solar-type star 51 Peg. Constraints originating from the observed rotational velocity of 51 Peg and from its low chromospheric emission give an upper limit of 2 M_J for the mass of the companion. Alternative explanations to the observed radial velocity variation (pulsation or spot rotation) are unlikely.

The very small distance between the companion and 51 Peg is certainly not predicted by current models of giant planet formation[8]. As the temperature of the companion is above 1,300 K, this object seems to be dangerously close to the Jeans thermal evaporation limit. Moreover, non-thermal evaporation effects are known to be dominant[9] over thermal ones. This jovian-mass companion may therefore be the result of the stripping of a very-low-mass brown dwarf.

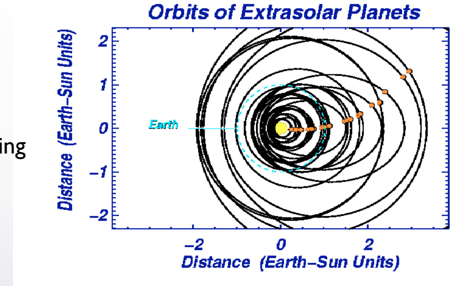
The short-period orbital motion of 51 Peg also displays a long-period perturbation, which may be the signature of a second low-mass companion orbiting at larger distance.

Discovery of Jupiter-mass companion(s)

Our measurements are made with the new fibre-fed echelle spectrograph ELODIE of the Haute-Provence Observatory, France[10]. This instrument permits measurements of radial velocity with an accuracy of about 13 m s^{-1} of stars up to 9 mag in an exposure time of <30 min. The radial velocity is computed

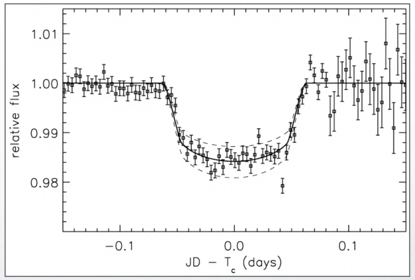
Radial velocities surveys

- Extremely successful
- Sensitivity keeps increasing
- Puzzling results



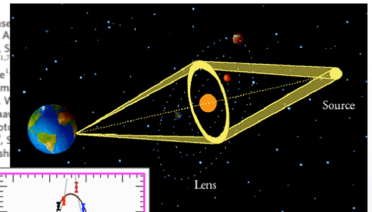
Transits

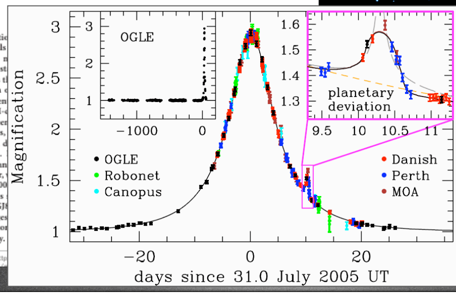
- Small (geometric) efficiency
- Requires tens of 1000s of stars
- Extremely fruitful:
  - radius, mass (RV)
    => density and composition
  - atmospheric composition
  - temperature(s)



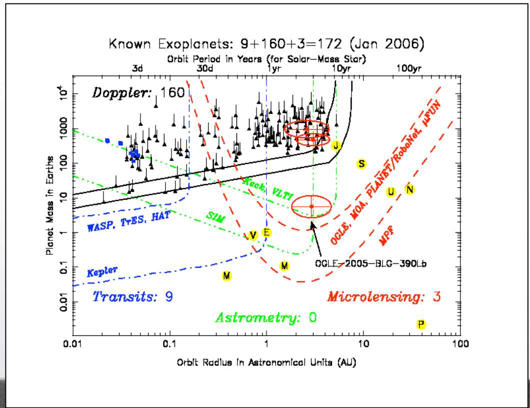
Microlensing

Discovery of a cool planet of 5.5 Earth masses through gravitational microlensing





Current results and expectations



Keith Horne

Fundamental physics that we'll use

- quantum physics:
  - degenerate gas
  - light-matter interactions
- electromagnetism, radiation laws
- thermodynamics
  - convection
- statistics

For extrasolar planets:

- Keplerian mechanics

Readings for next week: Spectral classification

- Popular:
  - *Die neuen Spektraltypen L und T*, Bailer-Jones & Bastian, Sterne & Weltraum, May 2004, p.20
- Book *New Light of dark stars*:
  - §§2.1, 2.2: quick introduction
  - §4: basic principles
- Professional literature: difficult, but try the introduction:
  - Kirkpatrick et al., ApJ **319**, p. 802 (1999), especially §5: L type
  - Martín et al., AJ **118**, p. 2466 (1999), especially §§3,4: L type
  - Burgasser et al., ApJ **637**, p.1067 (2006): §4: method, and §5: T type