AS3012: Exoplanetary Science

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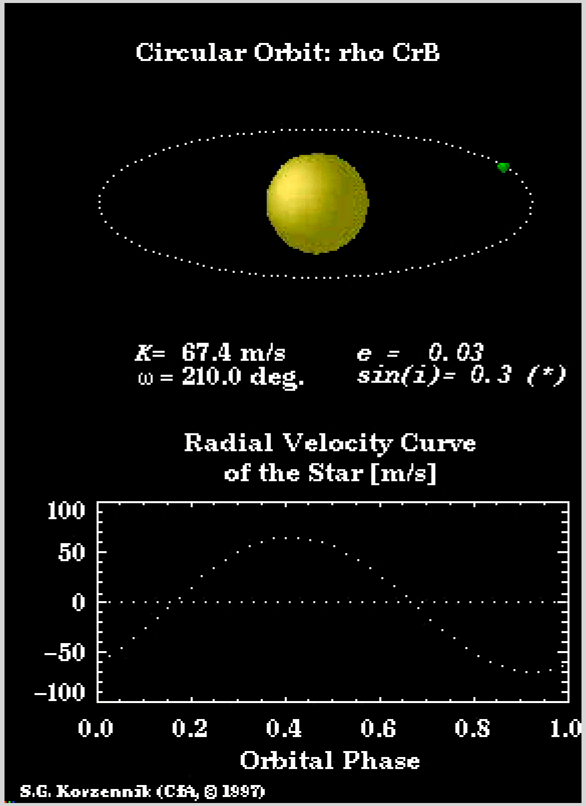
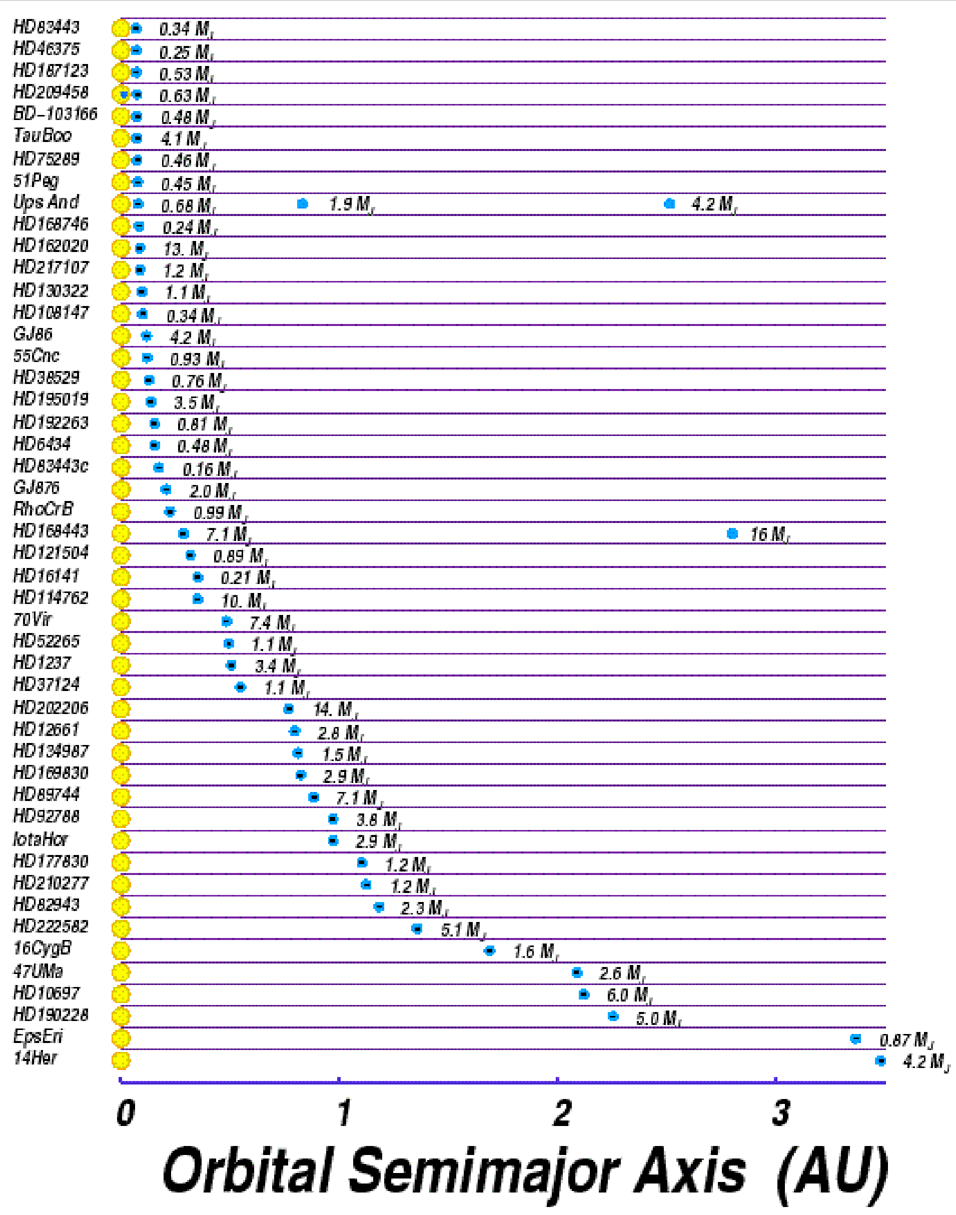
Room 226

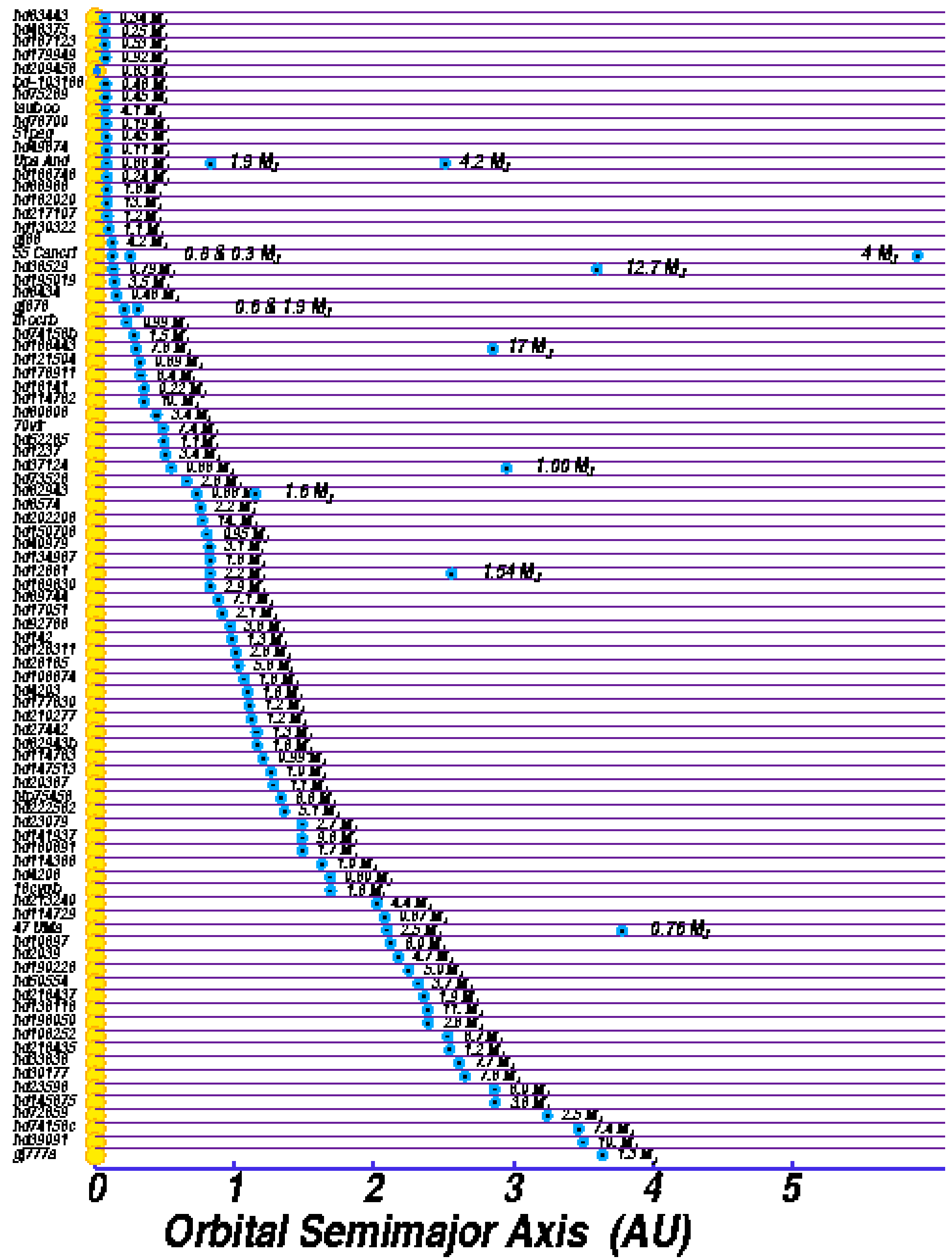
Radial velocities



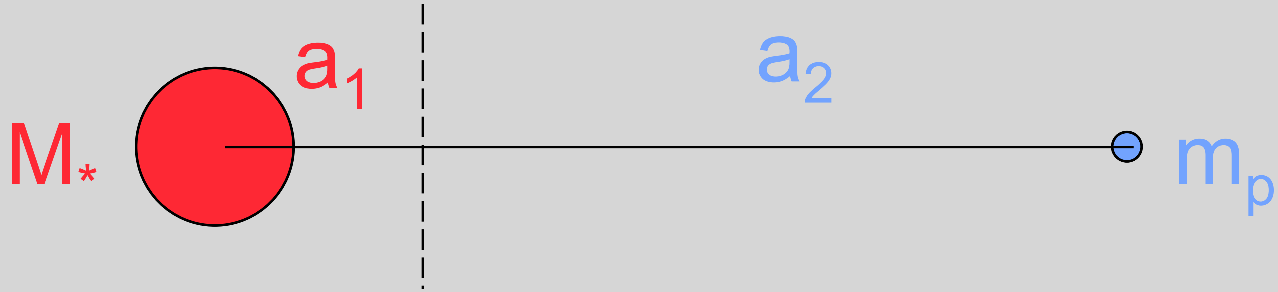
- Currently the most successful method used to detect exoplanets
- Method relies on the Doppler shift of starlight resulting from the star orbiting a common center of mass with a companion planet



HD83443
0.34 M_J
HD46375
0.25 M_J
HD187123
0.53 M_J
HD209458
0.63 M_J
BD-103166
0.48 M_J
TauBoo
4.1 M_J
HD75289
0.46 M_J
51Peg
0.45 M_J
Ups And
0.68 M_J
1.9 M_J
4.2 M_J
HD168746
0.24 M_J
HD162020
13. M_J
HD217107
1.2 M_J
HD130322
1.1 M_J
HD108147
0.34 M_J
GJ86
4.2 M_J
55Cnc
0.93 M_J
HD38529
0.76 M_J
HD195019
3.5 M_J
HD192263
0.81 M_J
HD6434
0.48 M_J
HD83443c
0.16 M_J
GJ876
2.0 M_J
RhoCrB
0.99 M_J
HD168443
7.1 M_J
16 M_J
HD121504
0.89 M_J
HD16141
0.21 M_J
HD114762
10. M_J
70Vir
7.4 M_J
HD52265
1.1 M_J
HD1237
3.4 M_J
HD37124
1.1 M_J
HD202206
14. M_J
HD12661
2.8 M_J
HD134987
1.5 M_J
HD169830
2.9 M_J
HD89744
7.1 M_J
HD92788
3.8 M_J
IotaHor
2.9 M_J
HD177830
1.2 M_J
HD210277
1.2 M_J
HD82943
2.3 M_J
HD222582
5.1 M_J
16CygB
1.6 M_J
47UMa
2.6 M_J
HD10697
6.0 M_J
HD190228
5.0 M_J
EpsEri
0.87 M_J
14Her
4.2 M_J
0
1
2
3
Orbital Semimajor Axis (AU)



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



Centre of mass of
binary system

Planet in circular orbit around star with semi-major axis a

Star and planet both rotate around the centre of mass with an angular velocity:

$$\Omega = \sqrt{\frac{G(M_* + m_p)}{a^3}}$$

Using $a_1 M_* = a_2 m_p$ and $a = a_1 + a_2$, stellar velocity in inertial frame is:

$$v_* \approx \left(\frac{m_p}{M_*}\right)\sqrt{\frac{GM_*}{a}}$$

(assuming $m_p << M_*$)

For a circular orbit, observe a sin-wave variation of the stellar radial velocity, with an amplitude that depends upon the inclination of the orbit to the line of sight:

$$v_{obs} = v_* \sin(i)$$

Hence, measurement of the radial velocity amplitude produces a constraint on:

$$m_p \sin(i)$$

(assuming stellar mass is well-known, as it will be since to measure radial velocity we need exceptionally high S/N spectra of the star)

Observable is a measure of $m_p \sin(i)$

-> given v_{obs}, obtain a lower limit to the planetary mass

In absence of other constraints on the inclination, radial velocity searches provide lower limits on planetary masses

Magnitude of radial velocity:

Sun due to Jupiter: 12.5 m/s

Sun due to Earth: 0.1 m/s

i.e. *extremely small* - 10 m/s is Olympic 100m running pace

Spectrograph with a resolving power of 10^5 will have a pixel scale of the order of 10^{-5} c ~ few km/s

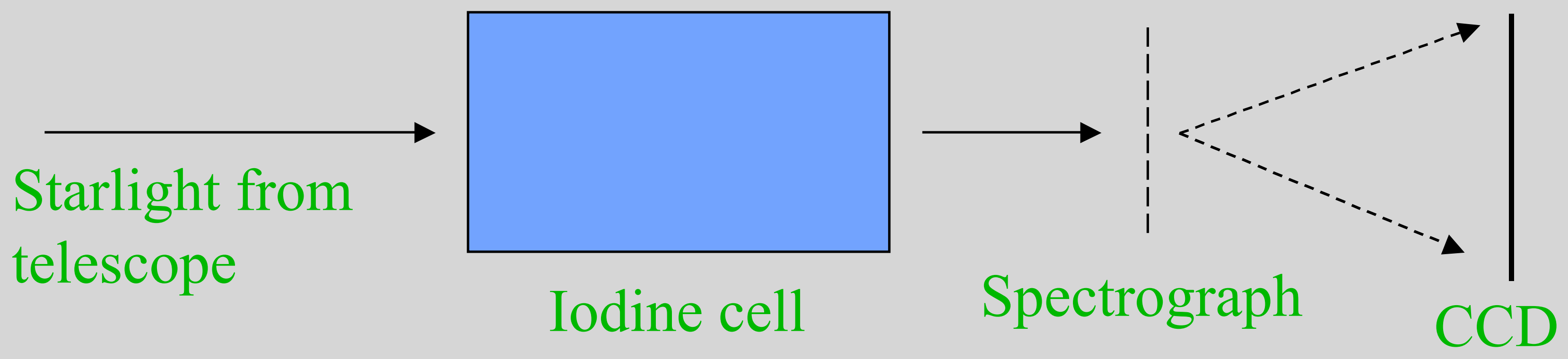
Specialized techniques that can measure radial velocity shifts of ~10^{-3} of a pixel stably over many years are required

High sensitivity to small radial velocity shifts:

- Achieved by comparing high S/N = 200 - 500 spectra with template stellar spectra
- Large number of lines in spectrum allows shifts of much less than one pixel to be determined

Absolute wavelength calibration and stability over long timescales:

- Achieved by passing stellar light through a cell containing iodine, imprinting large number of additional lines of known wavelength into the spectrum
- Calibration suffers identical instrumental distortions as the data



Error sources

(1) Theoretical: photon noise limit

- flux in a pixel that receives N photons uncertain by ~ $N^{1/2}$
- implies absolute limit to measurement of radial velocity
- depends upon spectral type - more lines improve signal
- around 1 m/s for a G-type main sequence star with spectrum recorded at S/N=200
- practically, S/N=200 can be achieved for V=8 stars on a 3m class telescope in survey mode

(2) Practical:

- stellar activity - young or otherwise active stars are not stable at the m/s level and cannot be monitored with this technique
- remaining systematic errors in the observations

Currently, best observations typically achieve:

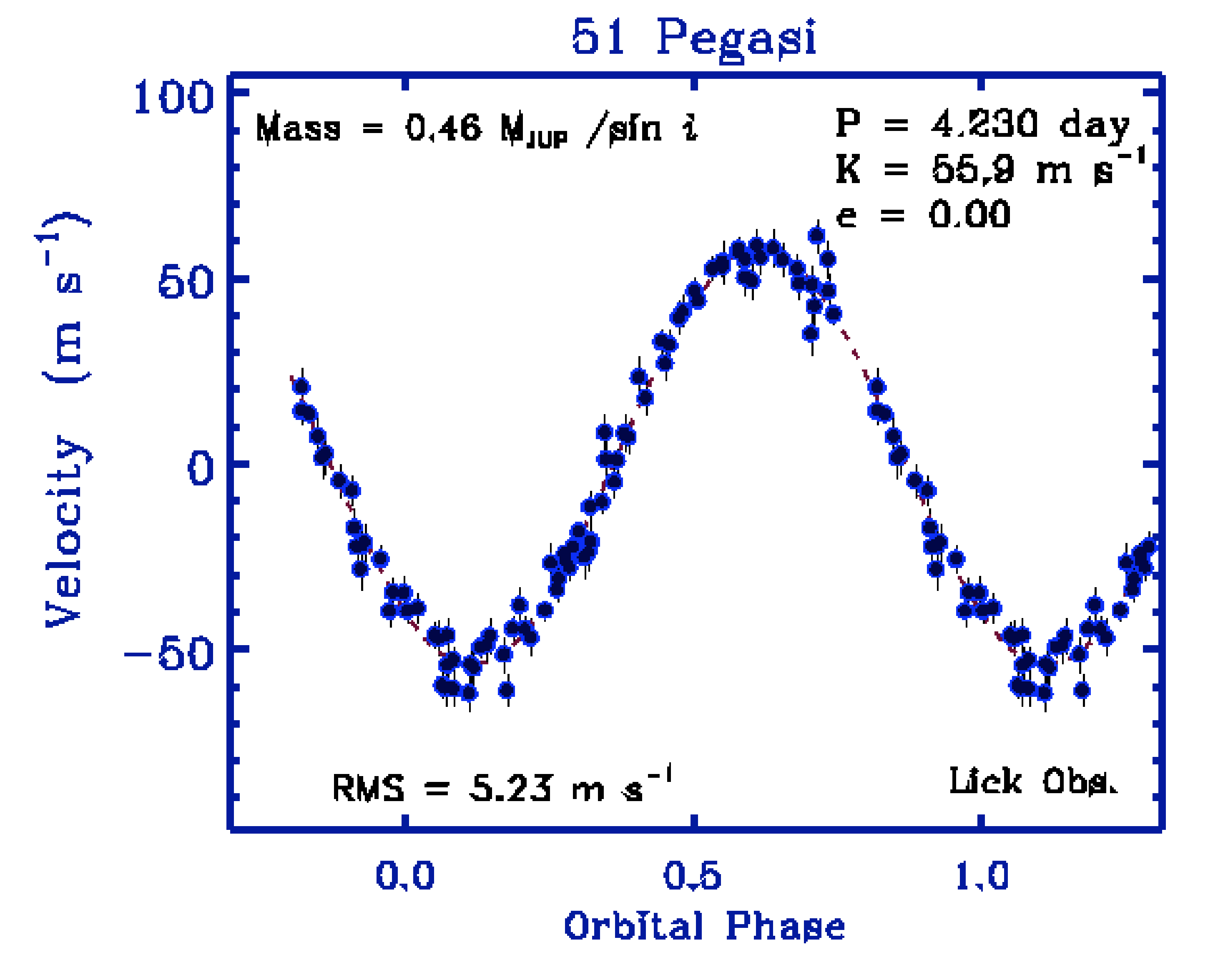
$$\sigma \approx 3 \text{ m/s}$$

...in a single measurement. However, the new high resolution echelle spectrograph HARPS (High Accuracy Radial velocity Planet Searcher) at the ESO La Silla 3.6m can achieve ≈ 1 m/s

47 Ursae Majoris c, inducing a radial velocity amplitude of 11.1 m/s, has one of the smallest amplitude wobbles so far attributed to a planet – the second planet to be found in this system!

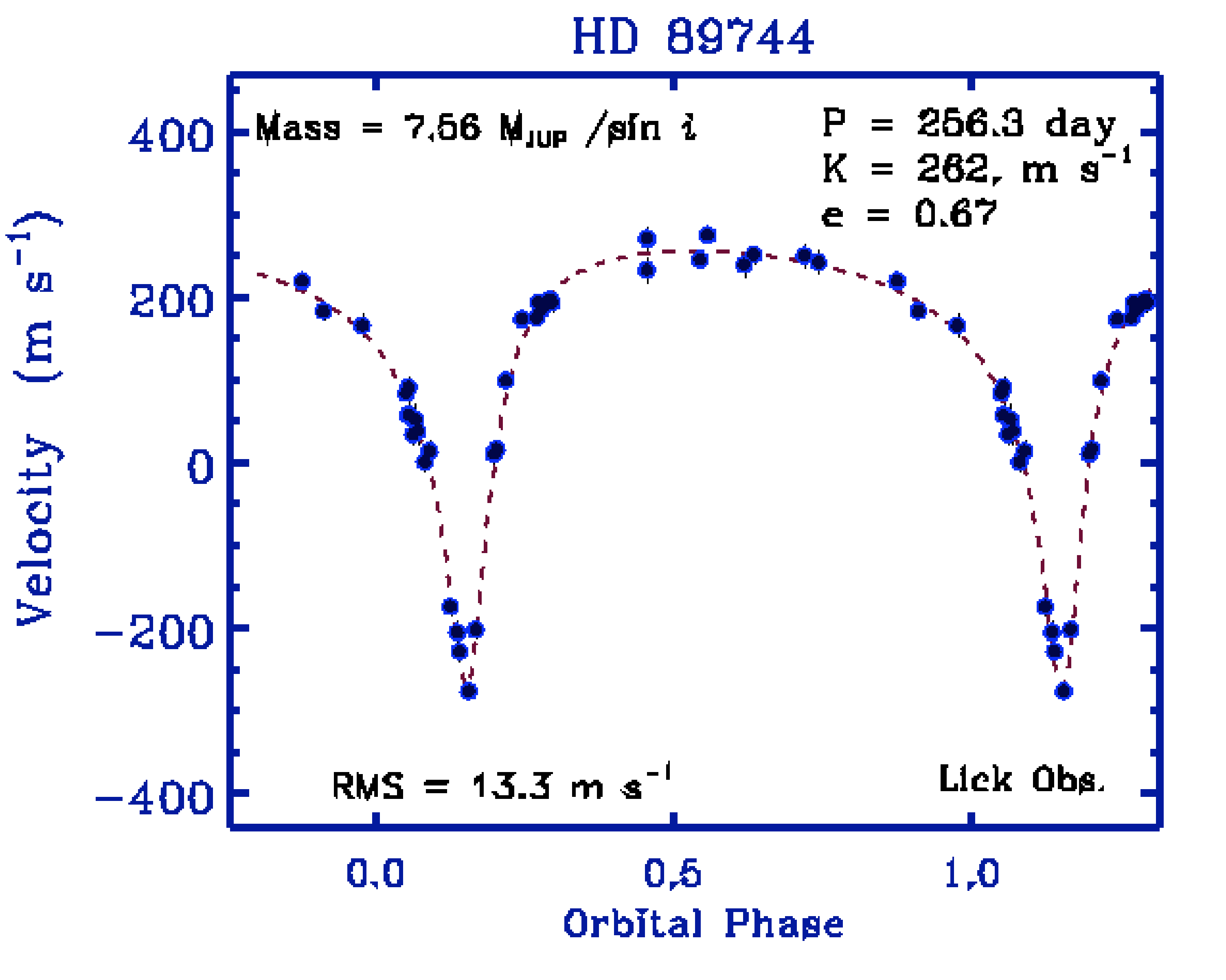
Radial velocity monitoring detects massive planets, especially those at small a, but is not sensitive enough to detect Earth-like planets at ~ 1 AU.

Examples of radial velocity data

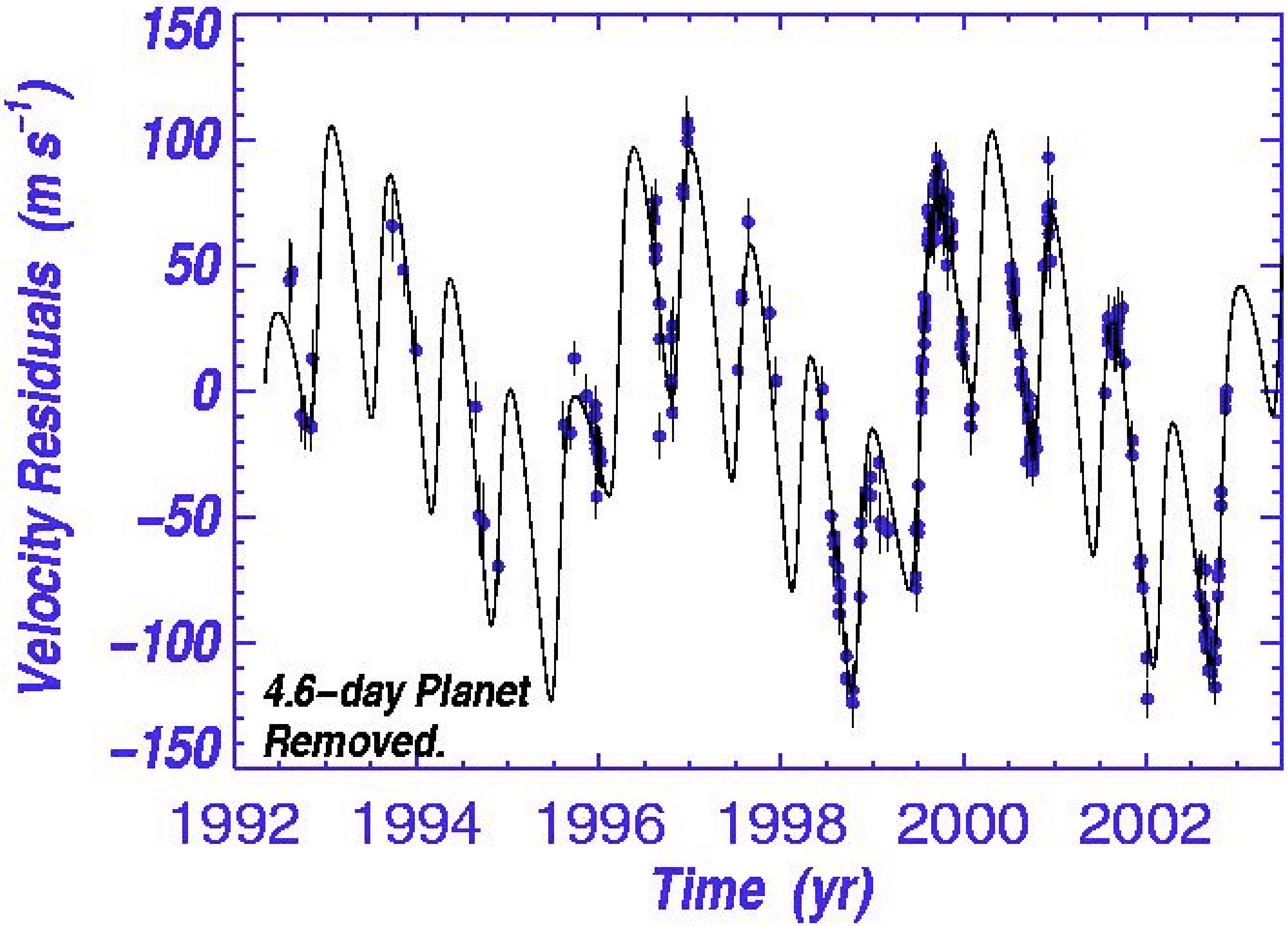


51 Peg, the first known exoplanet with a 4 day, circular orbit

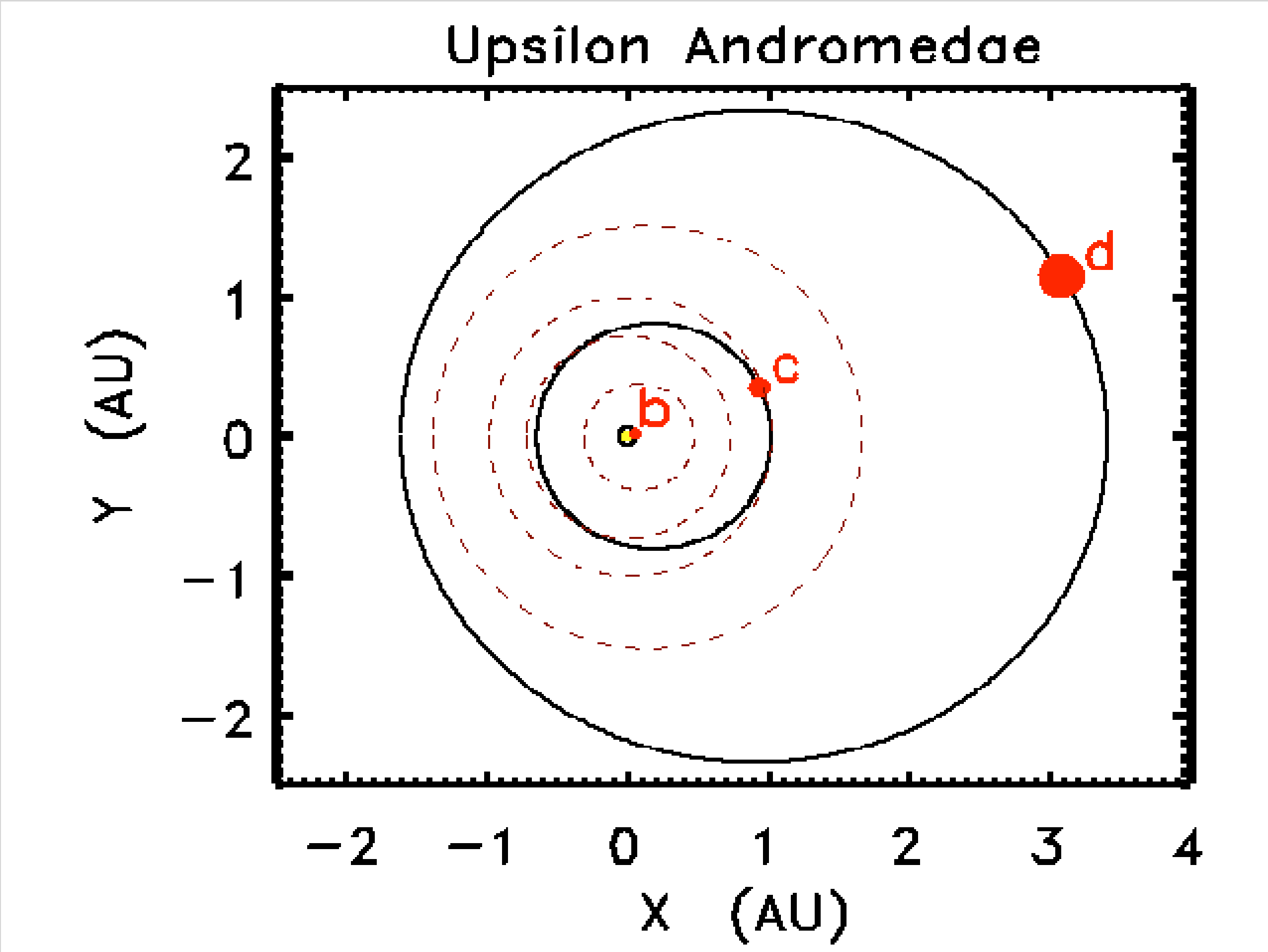
Example of a planet with an eccentric orbit: e=0.67



A Triple-Planet System Orbiting Upsilon Andromedae



A Triple-Planet System Orbiting Upsilon Andromedae



Summary: observables

(1) Planet mass, up to an uncertainty from the normally unknown inclination of the orbit. Measure $m_p \sin(i)$

(2) Orbital period -> radius of the orbit given the stellar mass

(3) Eccentricity of the orbit

Summary: selection function

Need to observe full orbit of the planet: zero sensitivity to planets with $P > P_{survey}$

For $P < P_{survey}$, minimum mass planet detectable is one that produces a radial velocity signature of a few times the sensitivity of the experiment (this is a practical detection threshold)

$$m_p \sin(i) \propto a^{1/2}$$

Which planets are detectable?