AST 301
Introduction to Astronomy

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Go to Department of Astronomy courses,

AST 301 (Lacy), course website

Topics for this week

- Area and volume
- Finding extrasolar planets
  - Imaging
  - Astrometric technique
  - Doppler technique
  - Transit technique
- What is found
  - Masses
  - Orbits
  - Densities and compositions
- Formation of extrasolar planets

Doppler technique

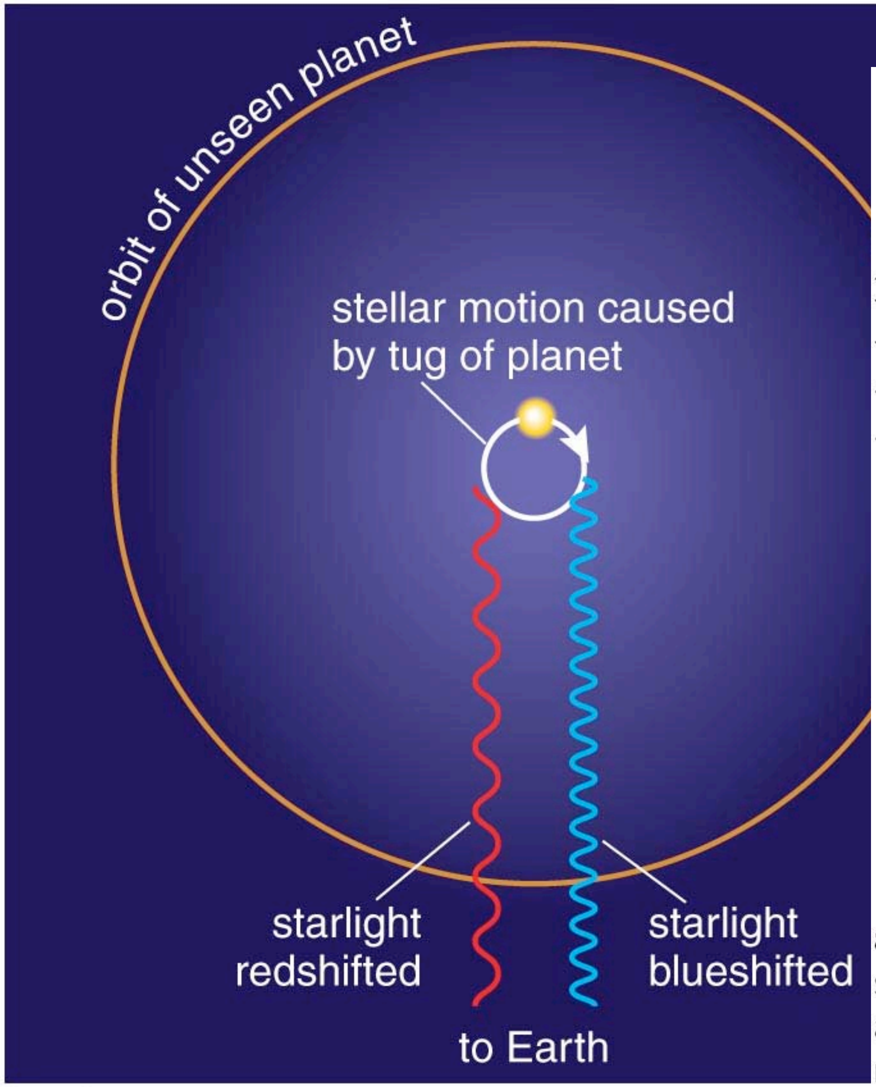
Measuring a motion in the sky of 0.001 arcseconds is almost as difficult as taking a picture of a planet.

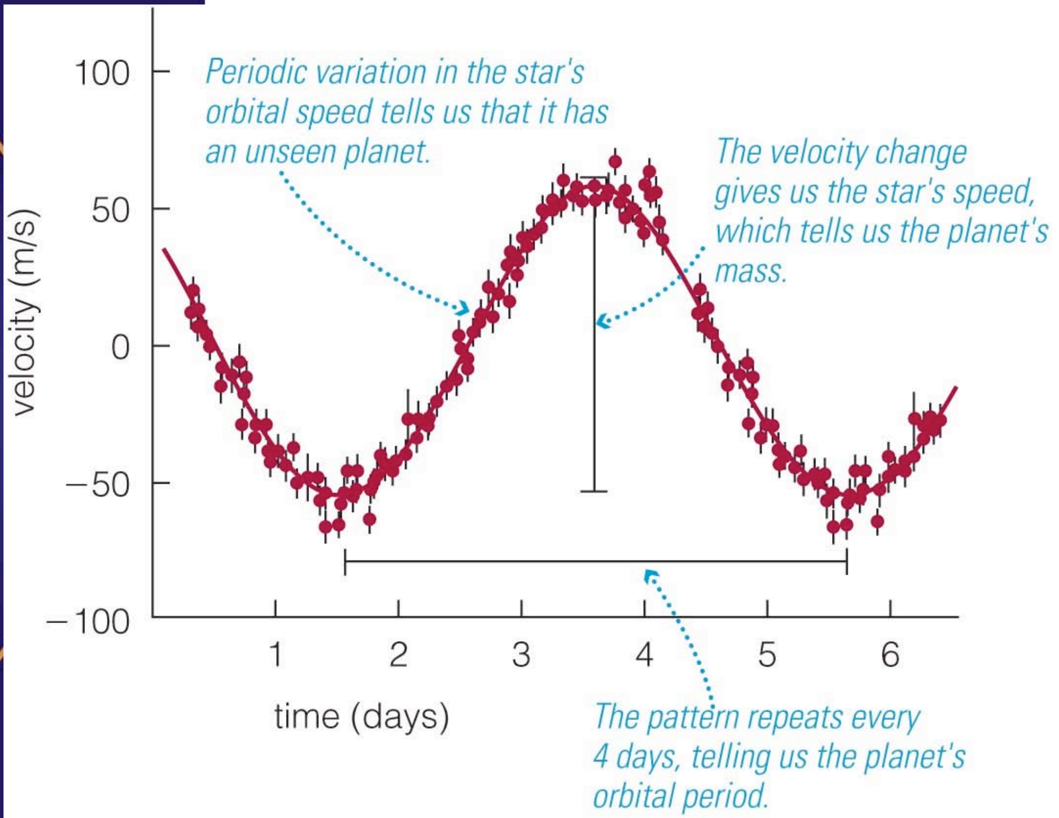
It turns out that it is easier to measure the Doppler shift of the star than it is to measure its change in position.

On your homework you will calculate the Doppler shift of the Sun caused by the pull of Jupiter.

It is small, but with some effort we can measure it.

Doppler shift of a star caused by a planet





a A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

What can we calculate?

The period of the planet's orbit is the time from one peak of the velocity curve to the next.

If we know the mass of the star, we can use Kepler's 3rd law to calculate the radius of the planet's orbit.

The distance the star travels in that time is the period times the speed, which is given by the maximum Doppler shift.

$d = vt$

This is the circumference of the star's orbit, and the radius of the star's orbit = circumference / 2π.

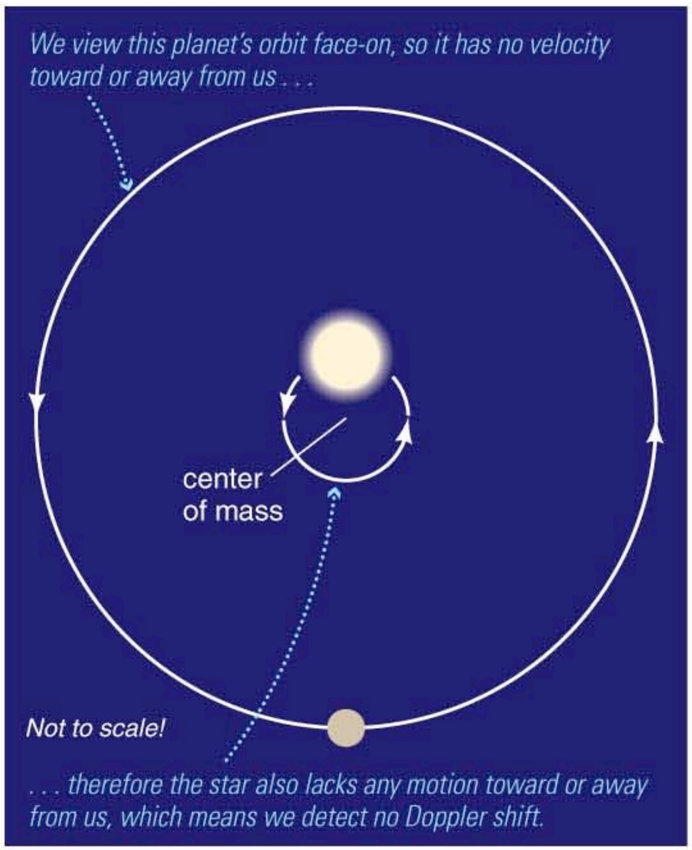
The ratio of the mass of the planet to the mass of the star equals the ratio of the radius of the star's orbit to the radius of the planet's orbit.

So we can learn both the mass of the planet and the size of its orbit.

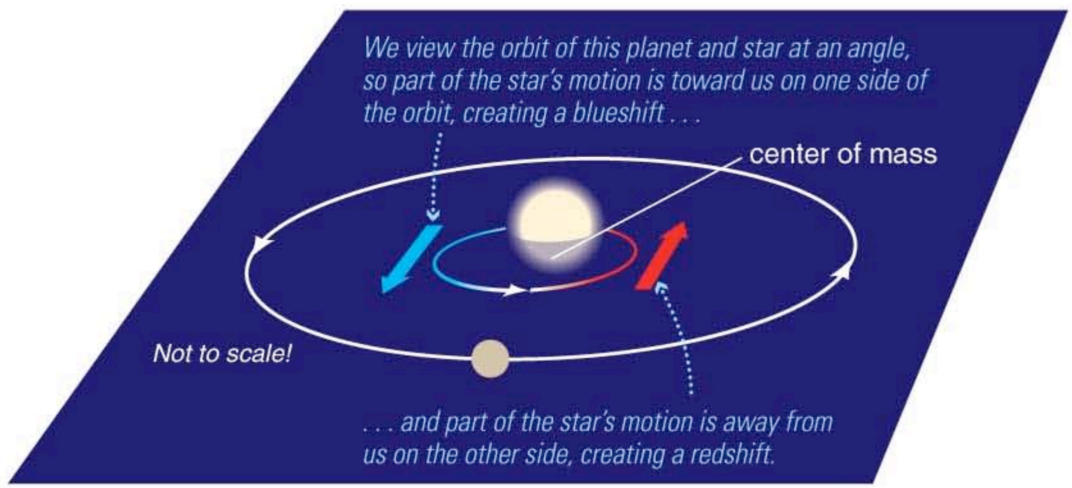
A complication

The Doppler shift also depends on how we view the orbit of the planet and its star.

We can't know this from just the Doppler shift.



a If we view a planetary orbit face-on, we will not detect any Doppler shift at all.



b We can detect a Doppler shift only if some part of the orbital velocity is directed toward or away from us. The more an orbit is tilted toward edge-on, the greater the shift we observe.

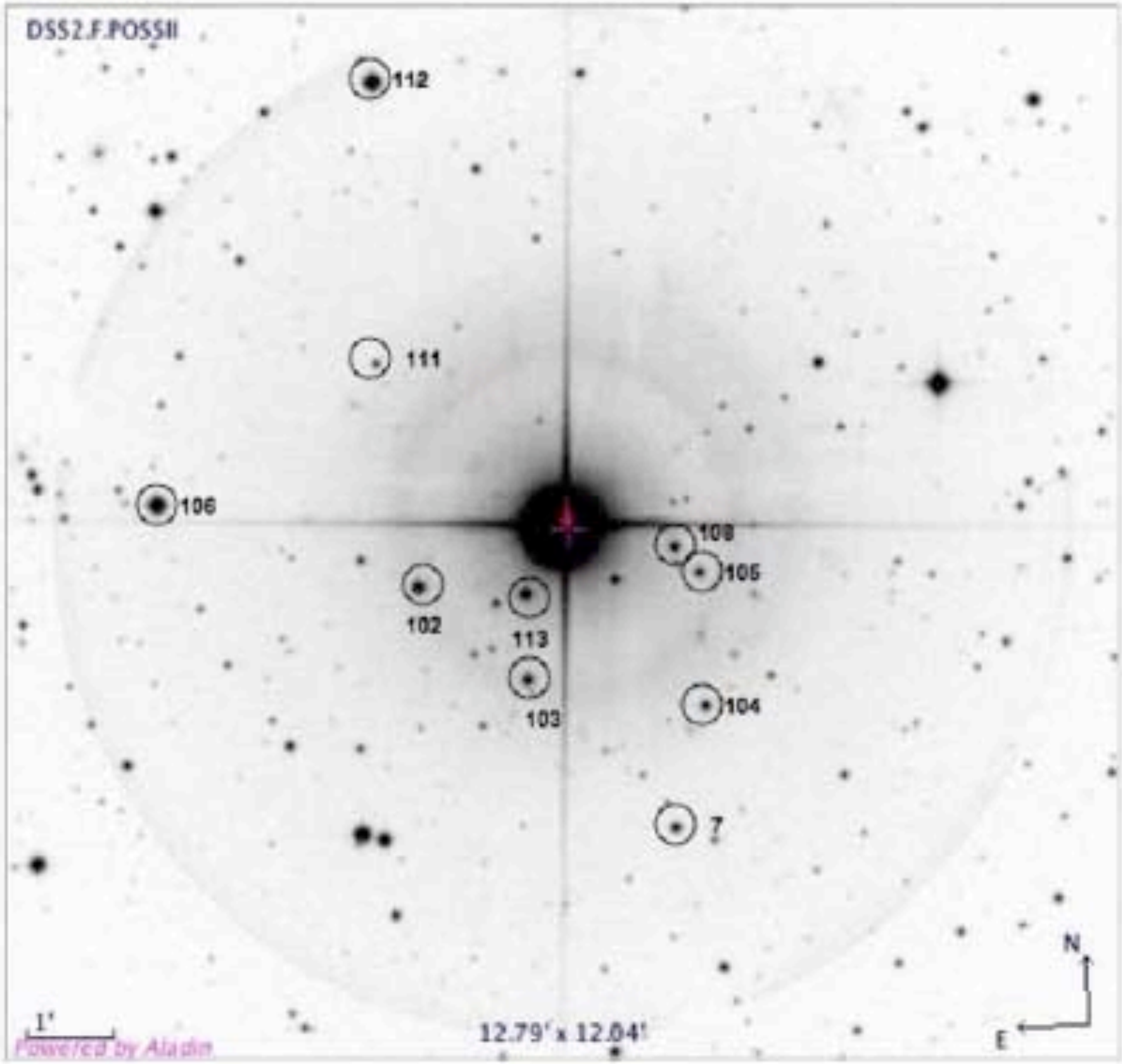


Figure 2. υ And field with astrometric reference stars marked. Reference star 113 is υ And B. The box is 15′ across.

Velocities derived from Doppler shifts

The original data has the Doppler shifts caused by the three planets combined.

They show them separately in this figure.

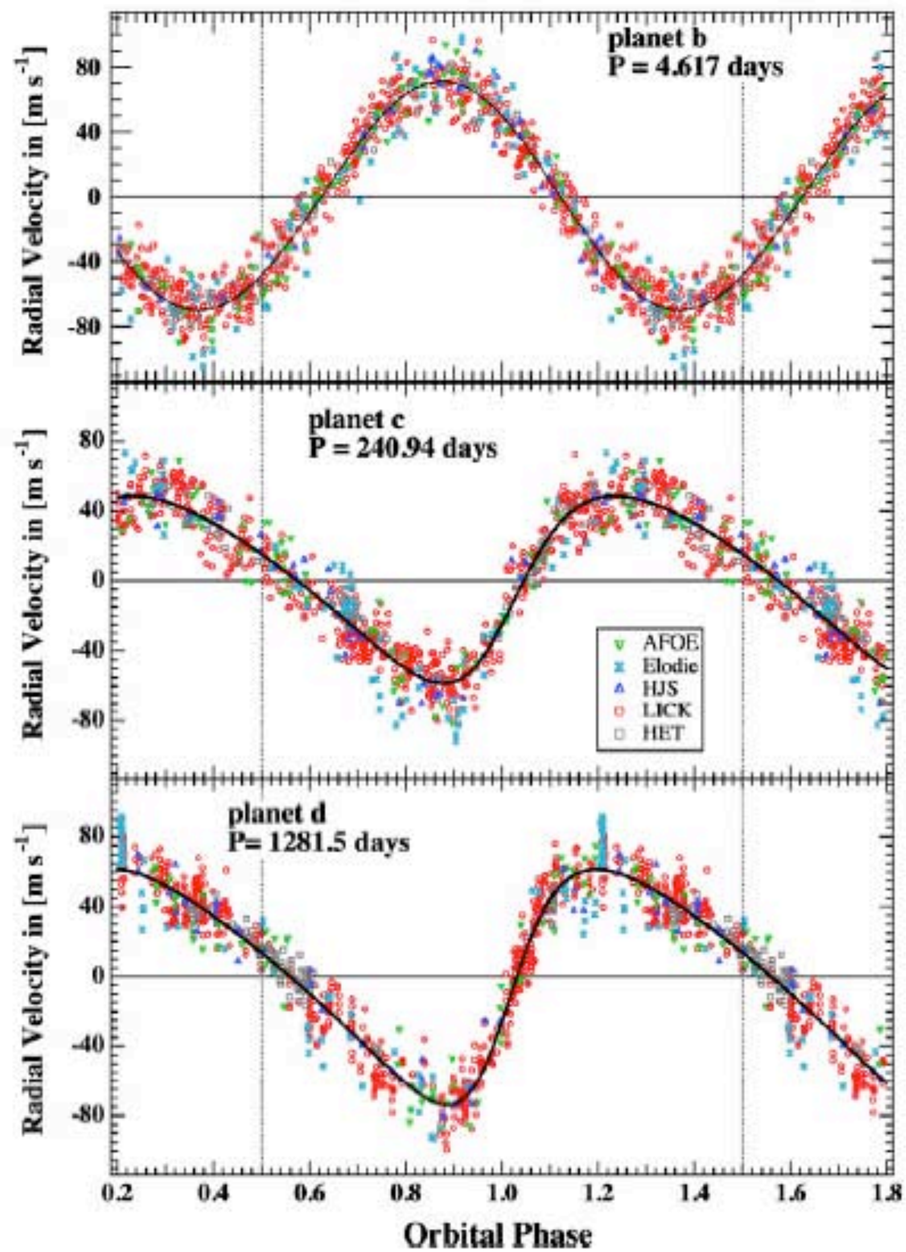


Figure 11. Residual velocities vs. orbital phase for each planet after the subtraction of the signal produced by the two other planets plus a linear trend.

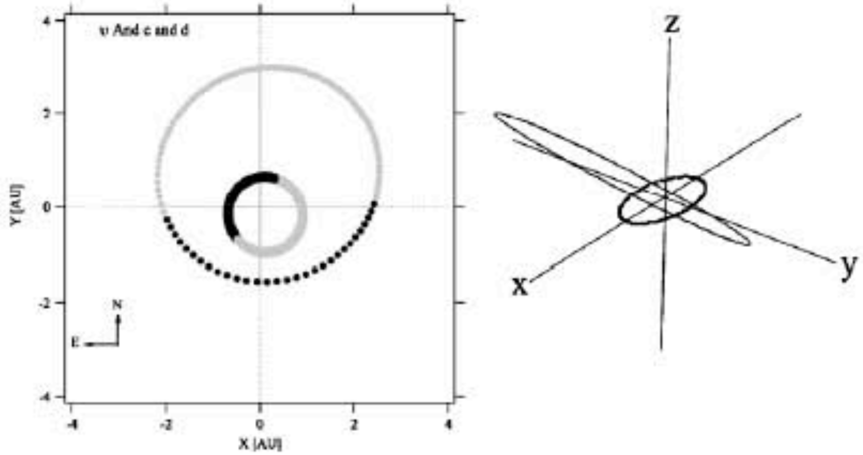
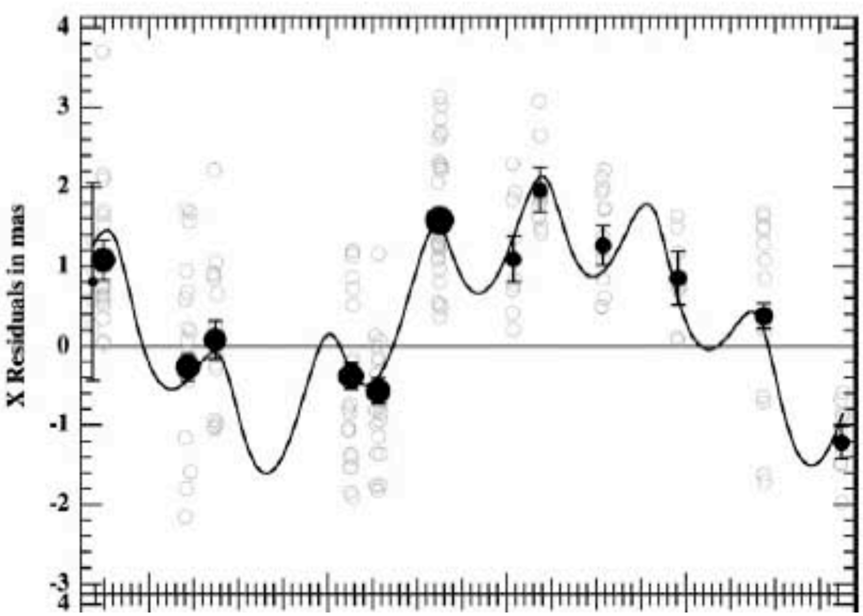


Figure 8. Left: orbits of υ And c and d on the sky. Darker segments of the orbits indicate out of plane, lighter behind plane of sky. Trace size is proportional to the masses of the companions. Right: perspective view of the orbits of components c and d projected on orthogonal axes.



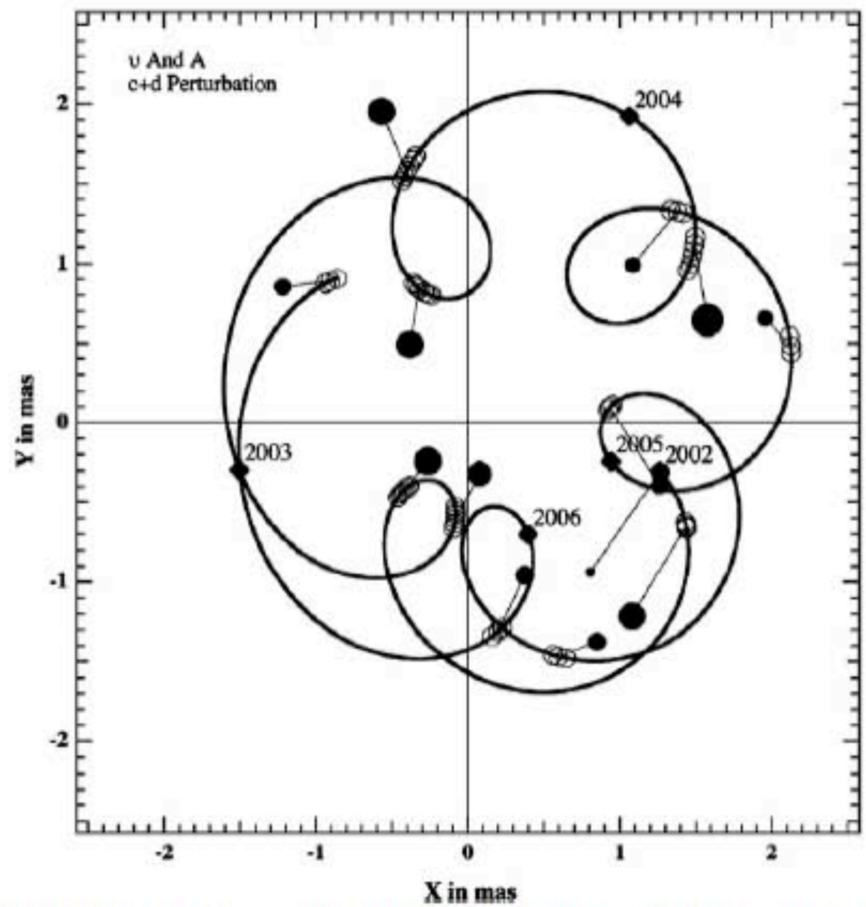


Figure 10. Astrometric reflex motion of υ And due to υ And c and d. The astrometric orbit is shown by the dark line. Open circles show times of observations, dark filled circles are normal points made from the υ And residuals to an astrometric fit of the target and reference frame stars of scale, lateral color, cross filter, parallax, and proper motion of multiple observations (light open circles) at each epoch. Normal point size is proportional to the number of individual measurements that formed the normal point. Solid line shows the combined astrometric motion of υ And c and d from the elements in Table 13.

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NEW OBSERVATIONAL CONSTRAINTS ON THE υ ANDROMEDAE SYSTEM WITH DATA FROM THE *HUBBLE SPACE TELESCOPE* AND HOBBY-EBERLY TELESCOPE*

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ABSTRACT

We have used high-cadence radial velocity (RV) measurements from the Hobby-Eberly Telescope with existing velocities from the Lick, Elodie, Harlan J. Smith, and Whipple 60″ telescopes combined with astrometric data from the *Hubble Space Telescope* Fine Guidance Sensors to refine the orbital parameters and determine the orbital inclinations and position angles of the ascending node of components υ And A c and d. With these inclinations and using $M_* = 1.31 M_\odot$ as a primary mass, we determine the actual masses of two of the companions: υ And A c is $13.98^{+2.3}_{-5.3}$ $M_{\rm JUP}$, and υ And A d is $10.25^{+0.7}_{-3.3}$ $M_{\rm JUP}$. These measurements represent the first astrometric determination of mutual inclination between objects in an extrasolar planetary system, which we find to be $29\overset{\circ}{.}9 \pm 1^\circ$. The combined RV measurements also reveal a long-period trend indicating a fourth planet in the system. We investigate the dynamic stability of this system and analyze regions of stability, which suggest a probable mass of υ And A b. Finally, our parallaxes confirm that υ And B is a stellar companion of υ And A.

Key words: astrometry – planetary systems – planets and satellites: dynamical evolution and stability – planets and satellites: fundamental parameters

Online-only material: color figures, machine-readable table

1. INTRODUCTION

υ Andromedae (υ And) is a sunlike F8 V star that is

and suggested that for parameters supported by the observations the system experienced chaotic evolution. They also concluded that N-body interactions alone could not have boosted υ And

Transit technique

There is yet another technique for finding planets around other stars.

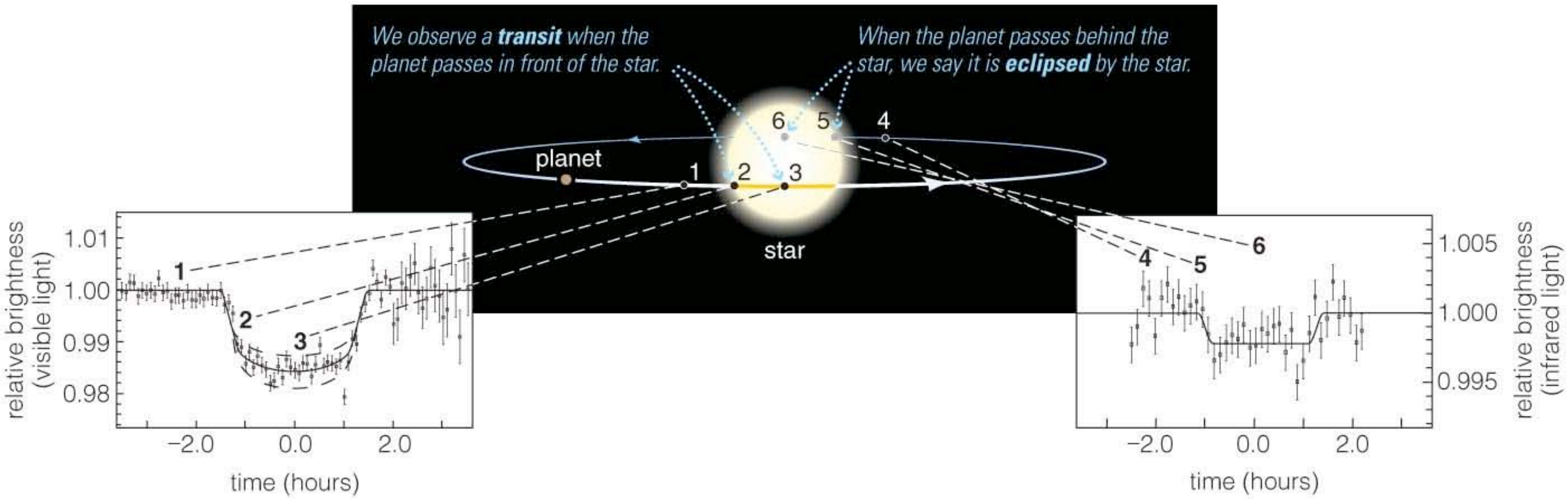
If the planet's orbit happens to make it pass between us and the star, it can block some of the starlight and make the star appear dimmer.

And if the planet passes behind the star, the planet's light (either reflected starlight or emitted infrared light) can be blocked by the star.

If you were observing the Sun from far away and Jupiter passed between you and the Sun, how much of the Sun's light would be blocked?

Hint: Jupiter's diameter is 1/10 the Sun's diameter.

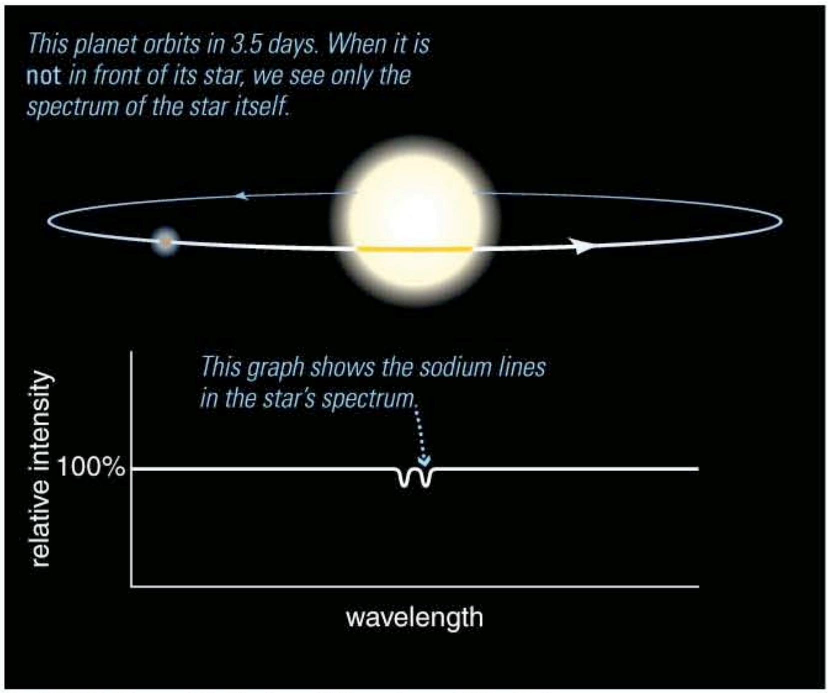
Transit technique

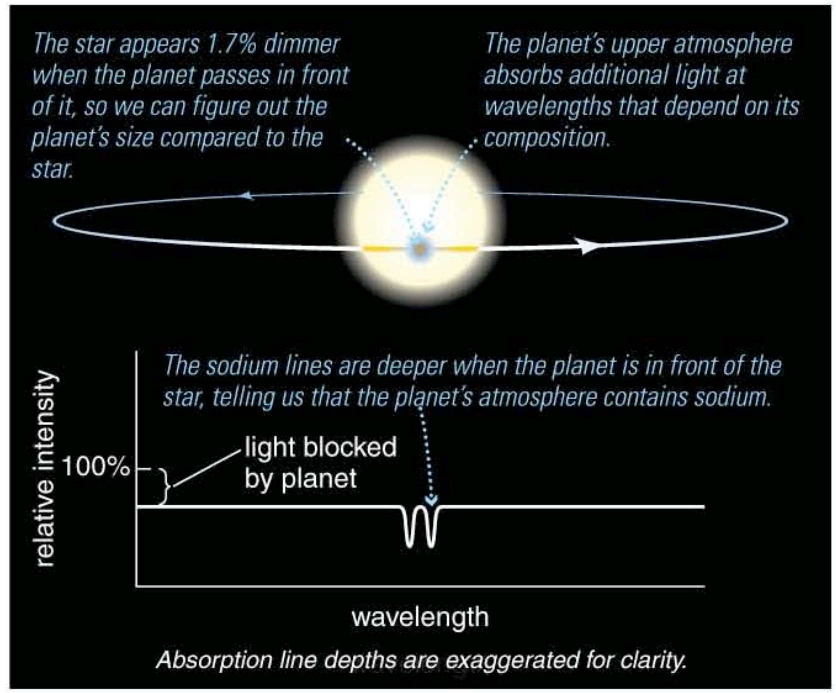


How large is this planet?

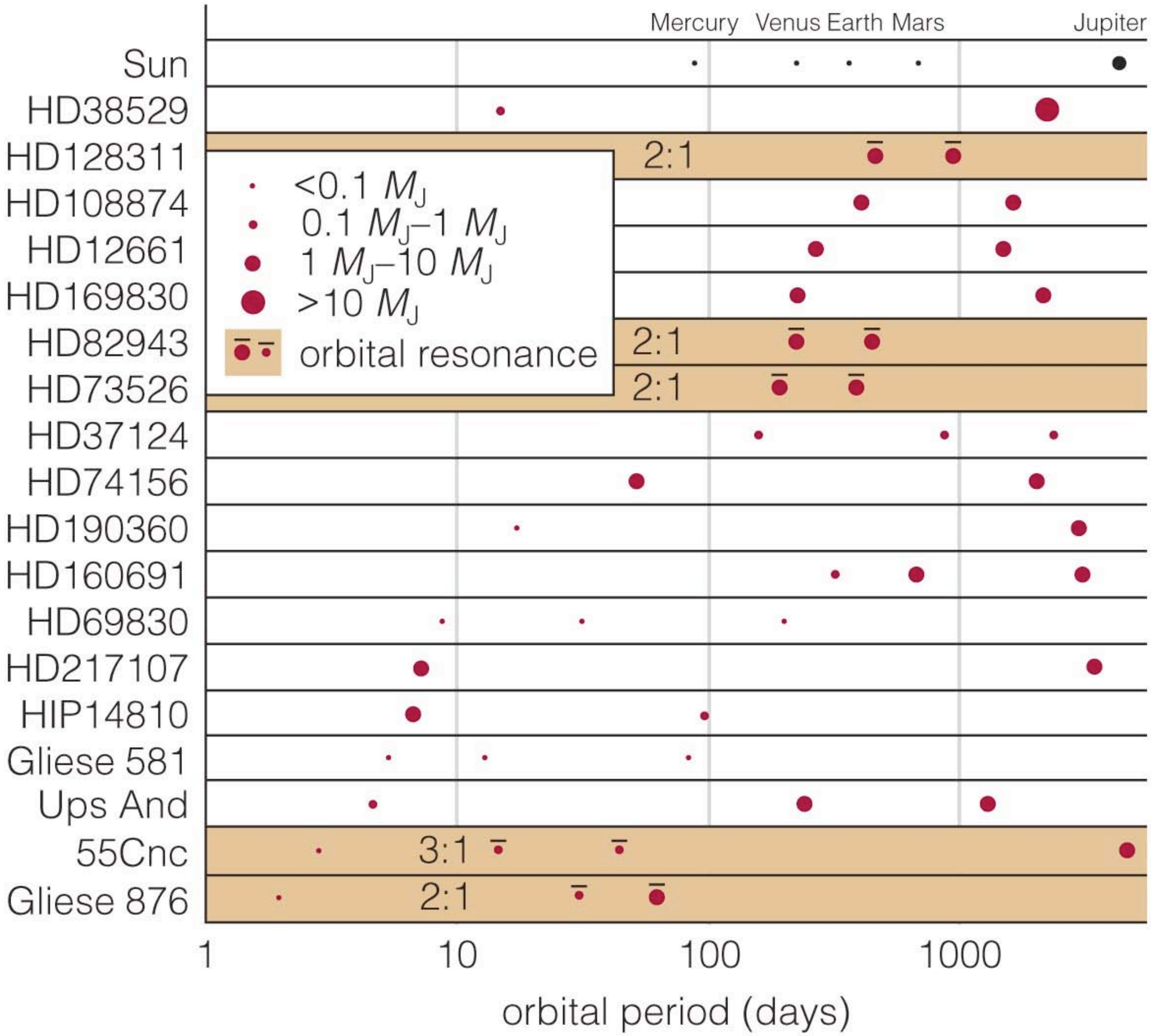
How bright is its surface compared to its star’s surface?

Composition of a planet's atmosphere

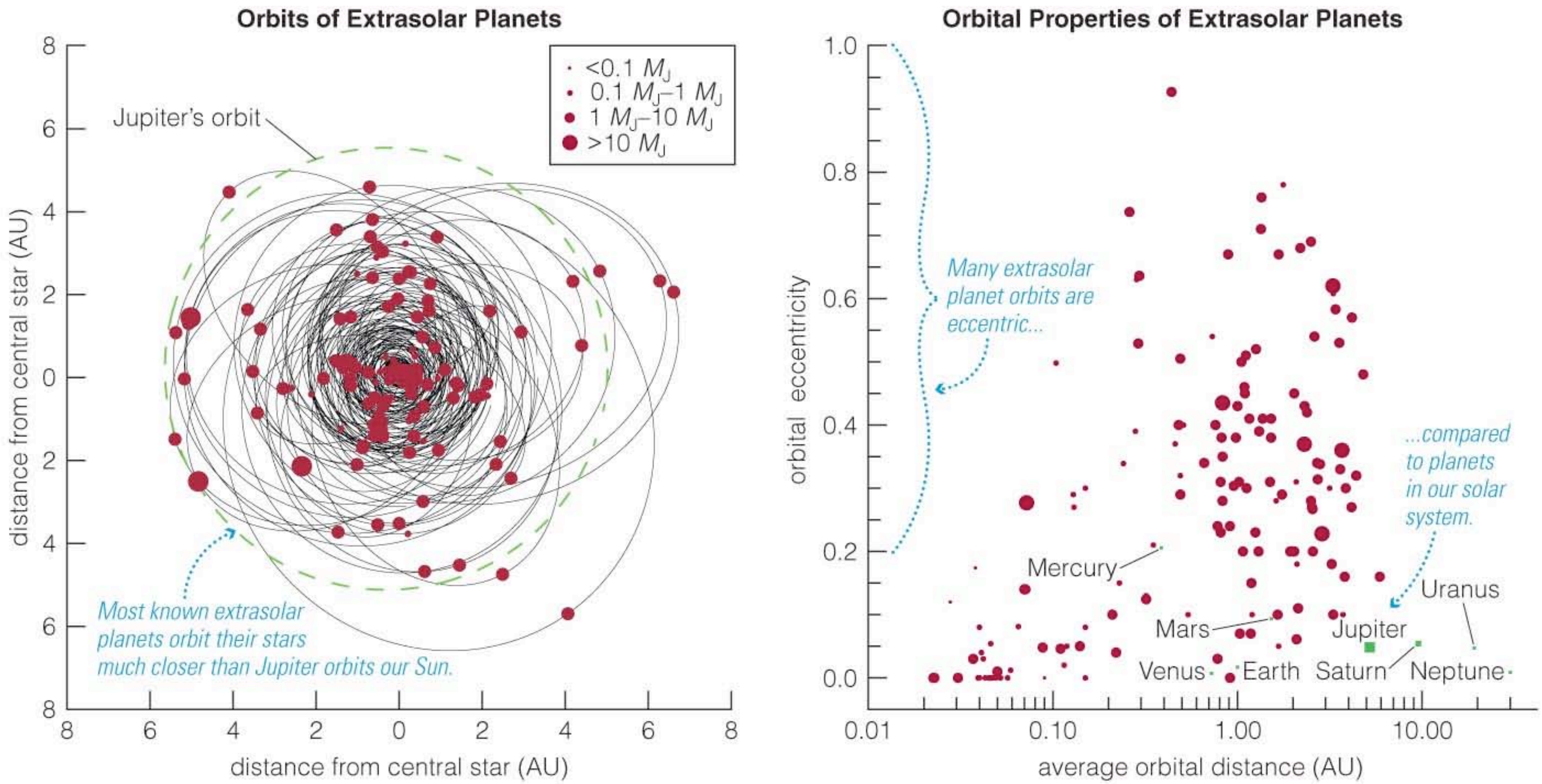




What sorts of planets have we found?



What are their orbits like?



a This diagram shows all the orbits superimposed on each other, as if all the planets orbited a single star. Dots are located at the aphelion (farthest) point for each orbit, and their sizes indicate minimum masses of the planets.

b The data from (a) are shown here as a graph. Dots closer to the left represent planets that orbit closer to their stars, and dots lower down represent smaller orbital eccentricities. Green dots are planets of our own solar system.