PTYS 568

Exoplanets: Discovery & Characterization

Class basics:

- No traditional "homework" (but lots of reading, etc.)
- Presentations (50%)
- Projects (50%)
- Likely no final

Course Outline:

- Pt. 1 (Discovery)
  - RV, Transits, Astrometry, Direct Imaging ...
- Pt. 2 (Atmospheres/Interiors)
  - rad. transfer, chemistry, opacities, ...
- Pt. 3 (Exoplanet Characterization)
  - structure, photometry, spectroscopy, ...

Finding Exoplanets

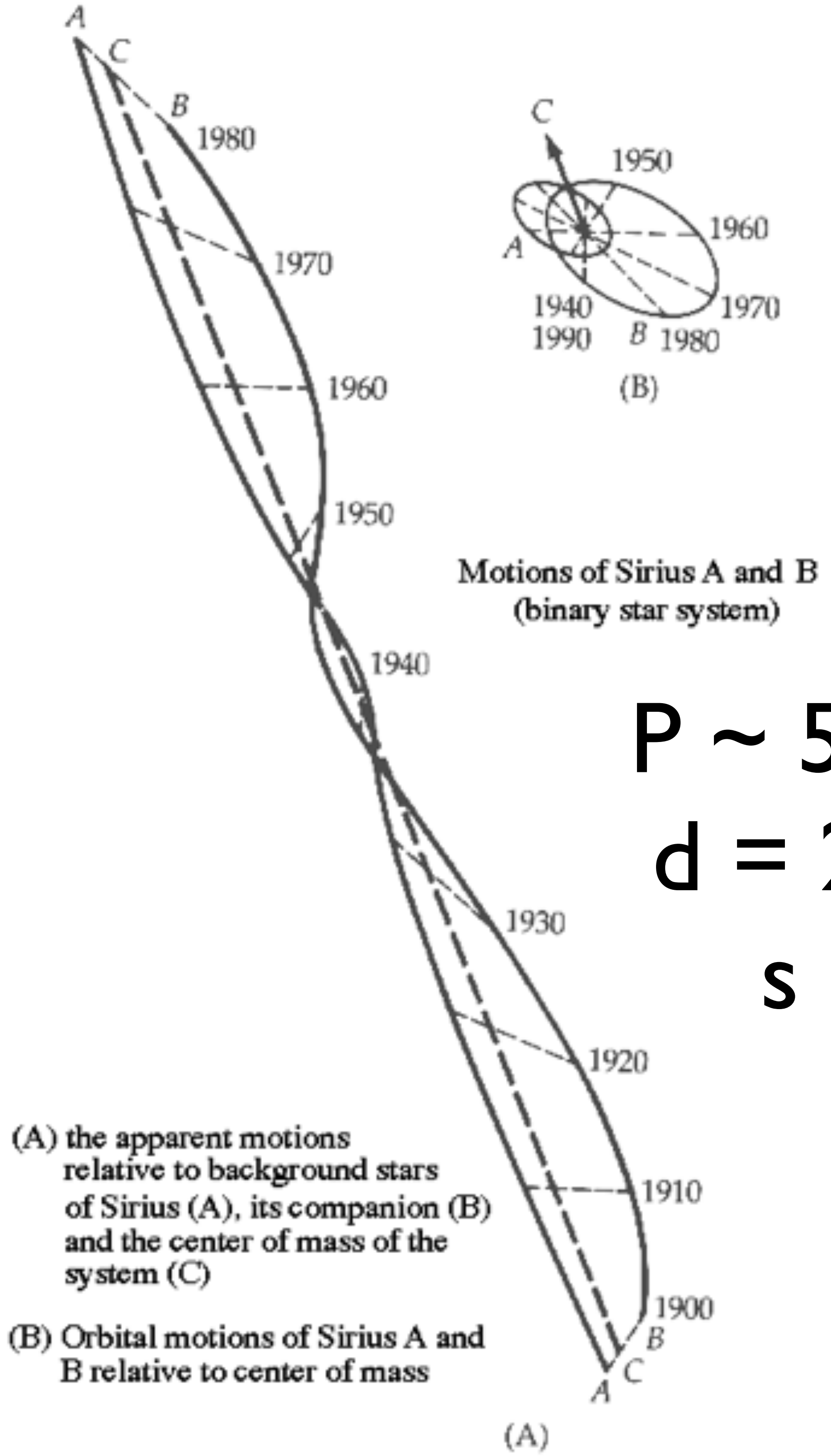
- In comparison to stars, planets are faint, small and low mass.
- If Jupiter orbited alpha-Centauri, it would be 4" from and 10^9 times fainter than the host star. (imaging is feasible, if scattered light can be removed — challenging.)
- Indirect techniques that rely on *stellar photons* will always be more efficient for surveys.

- The expectation of finding “Exoplanets” has been around much longer than the 90s.

- The transit, radial velocity, and astrometric techniques for finding planets were *all adopted from the field of binary stars*.

- https://link.springer.com/referencework/10.1007%2F978-3-319-55333-7

Visual Binaries and Astrometry



Motions of Sirius A and B
(binary star system)

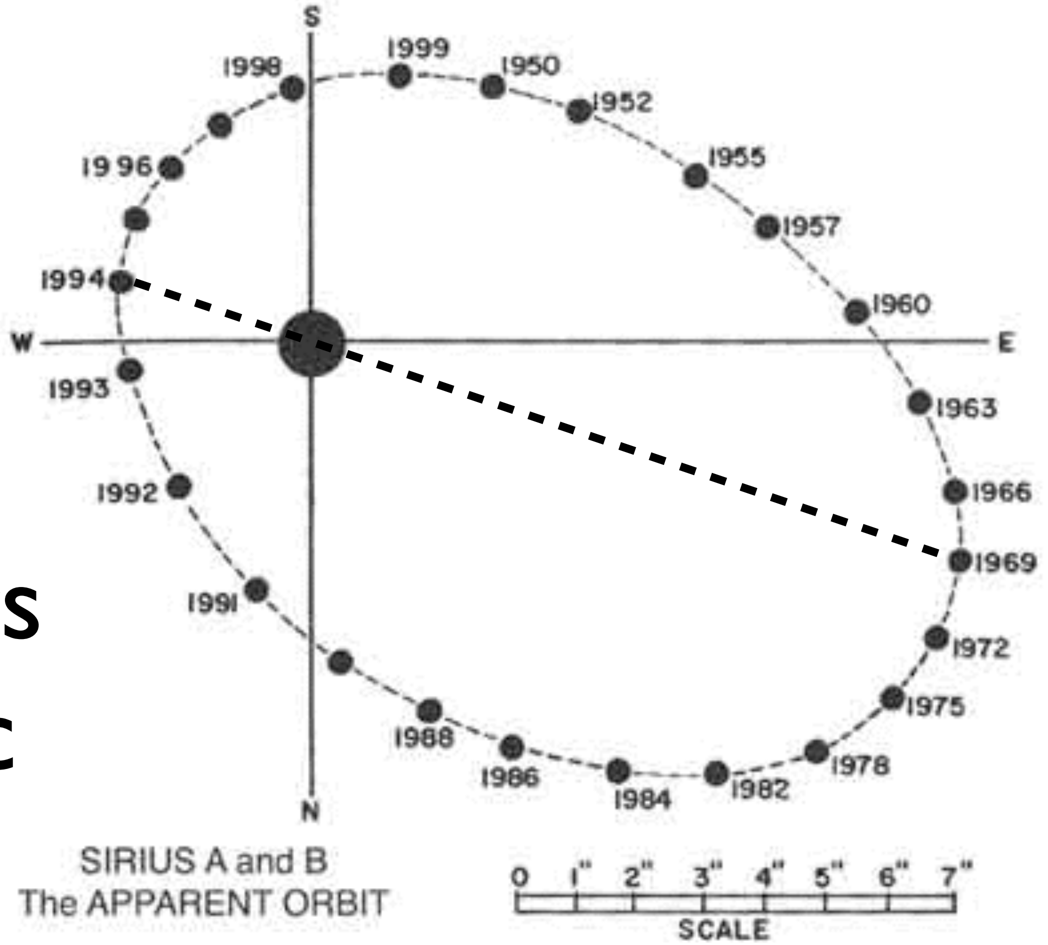
(A) the apparent motions relative to background stars of Sirius (A), its companion (B) and the center of mass of the system (C)

(B) Orbital motions of Sirius A and B relative to center of mass

P ~ 50 years

d = 2.64 pc

s ~ 7”



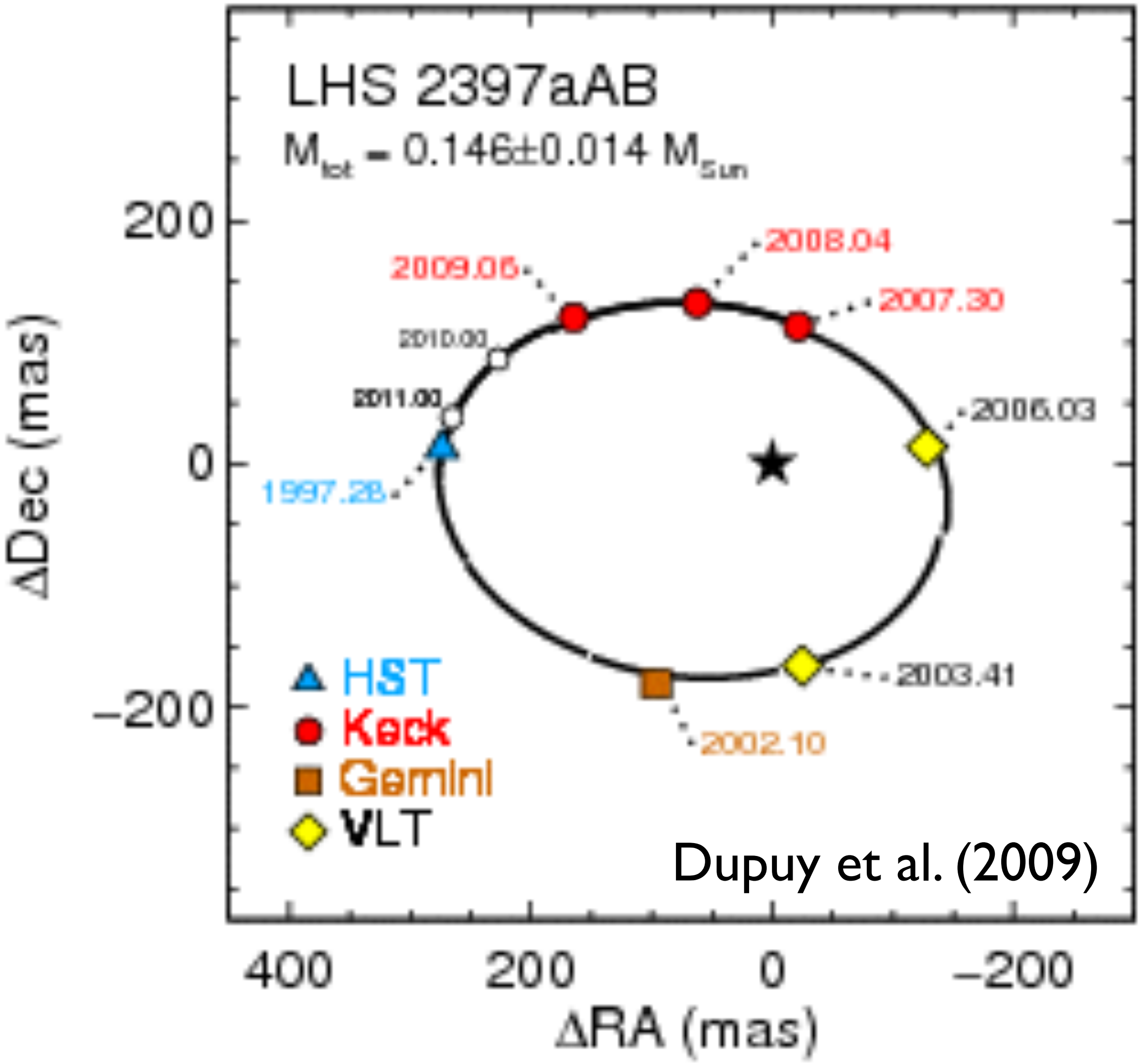
SIRIUS A and B
The APPARENT ORBIT

$$M_1 + M_2 = \frac{4\pi^2}{G}\frac{a^3}{P^2}$$

$$M_1 + M_2 = d^3 s^3 / P^2$$

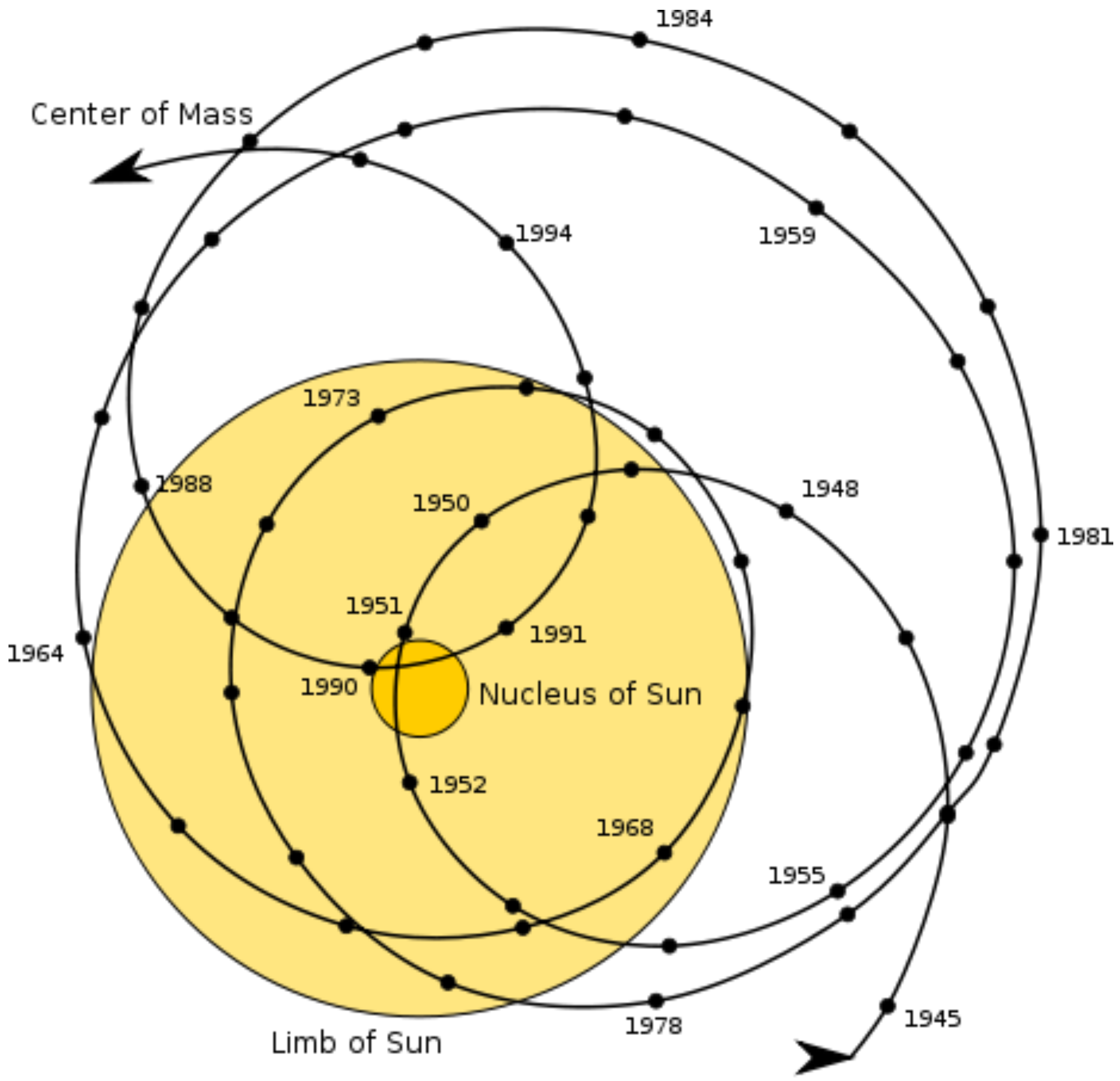
[ignoring sin(i)]

also possible for massive brown dwarfs



Dupuy et al. (2009)

How large is the wobble induced by Jupiter?



Sun Jupiter

$$M_1 a_1 = M_2 a_2$$

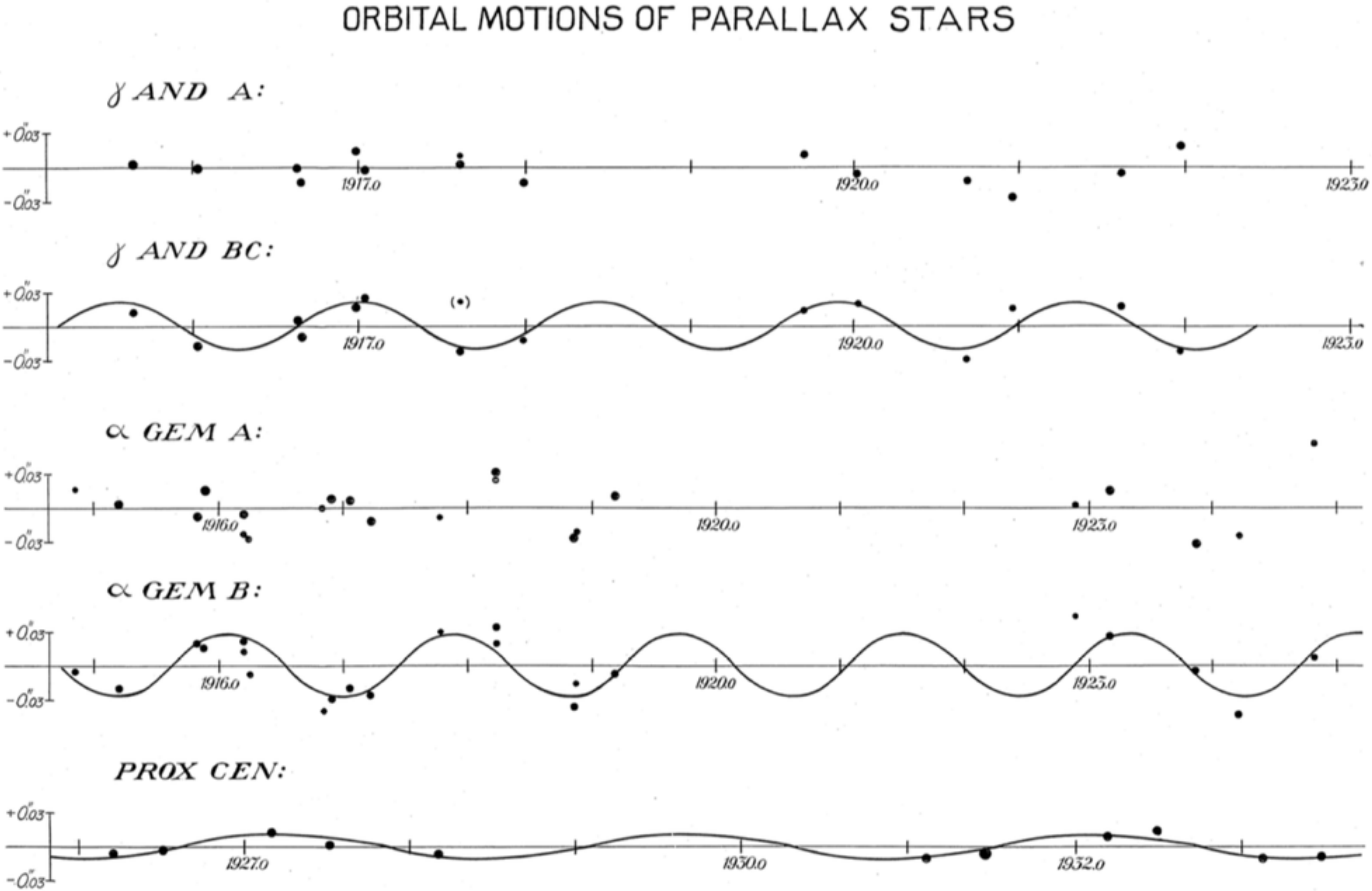
$$a_1 \sim \frac{a_2}{1000}$$

$$a_1 \sim 0.005\mathrm{AU}$$

$$\sim 7 \times 10^{10}\mathrm{cm}(\sim R_\odot)$$

you need sub-milliarcsec precision (GAIA)

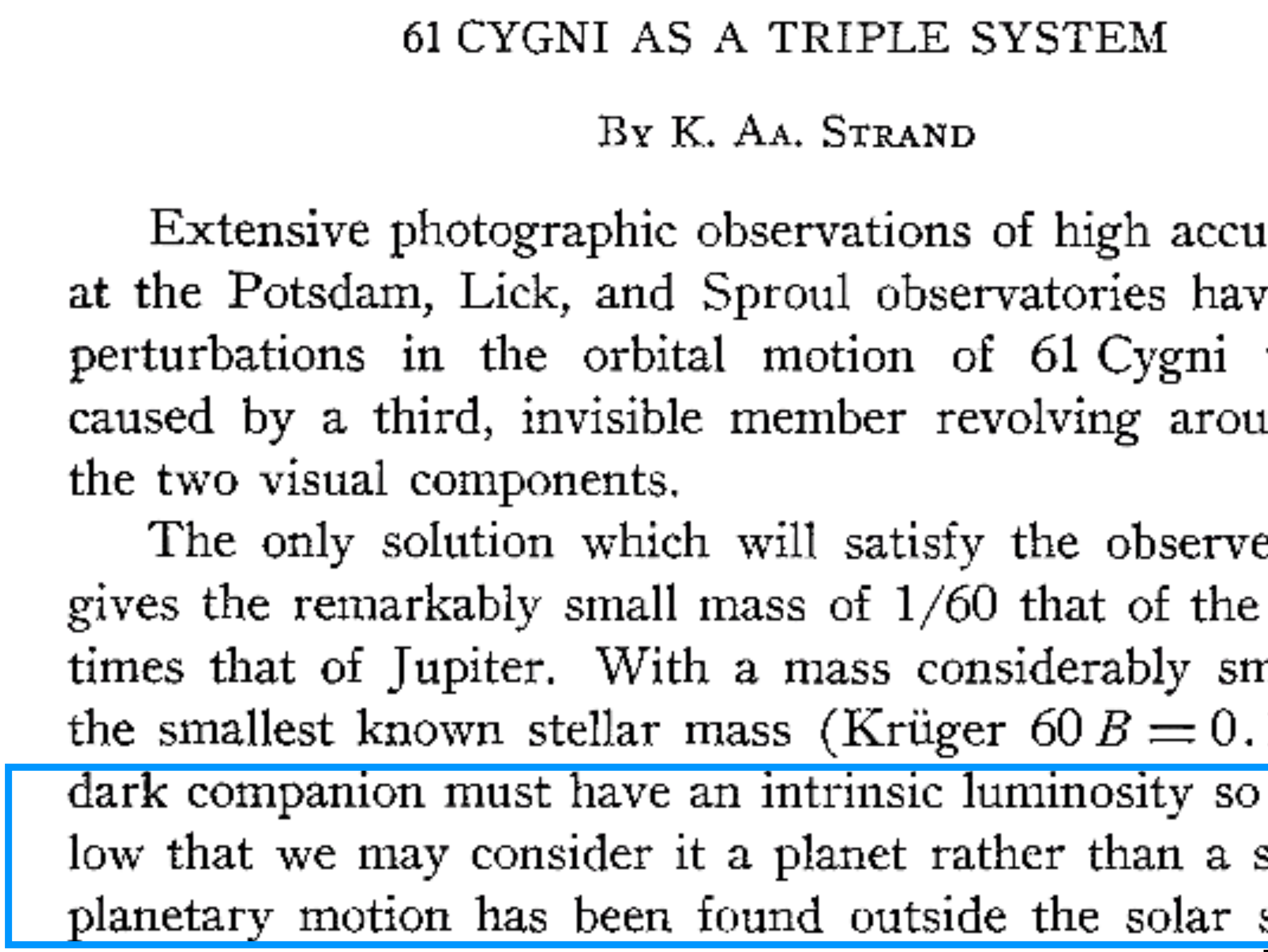
(1938, false detection)



“evidence” of ~ Jupiter-mass companion

Holmberg 1938

1942, false detection of a “dark companion”

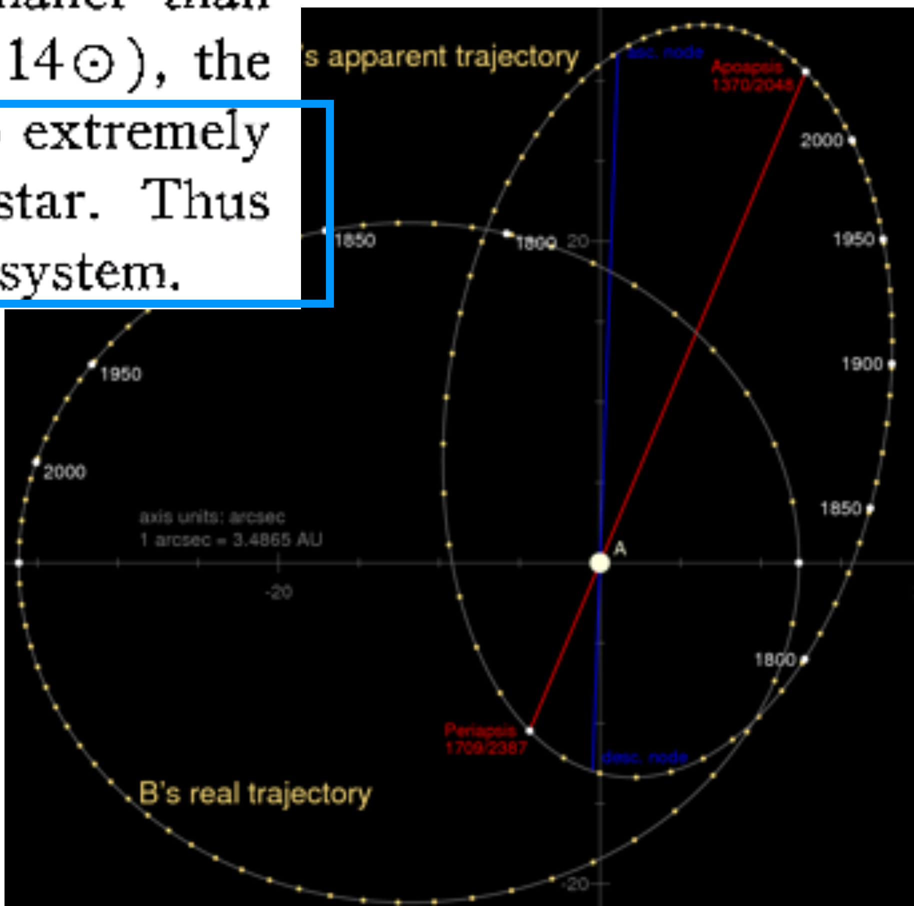


61 CYGNI AS A TRIPLE SYSTEM

By K. Aa. Strand

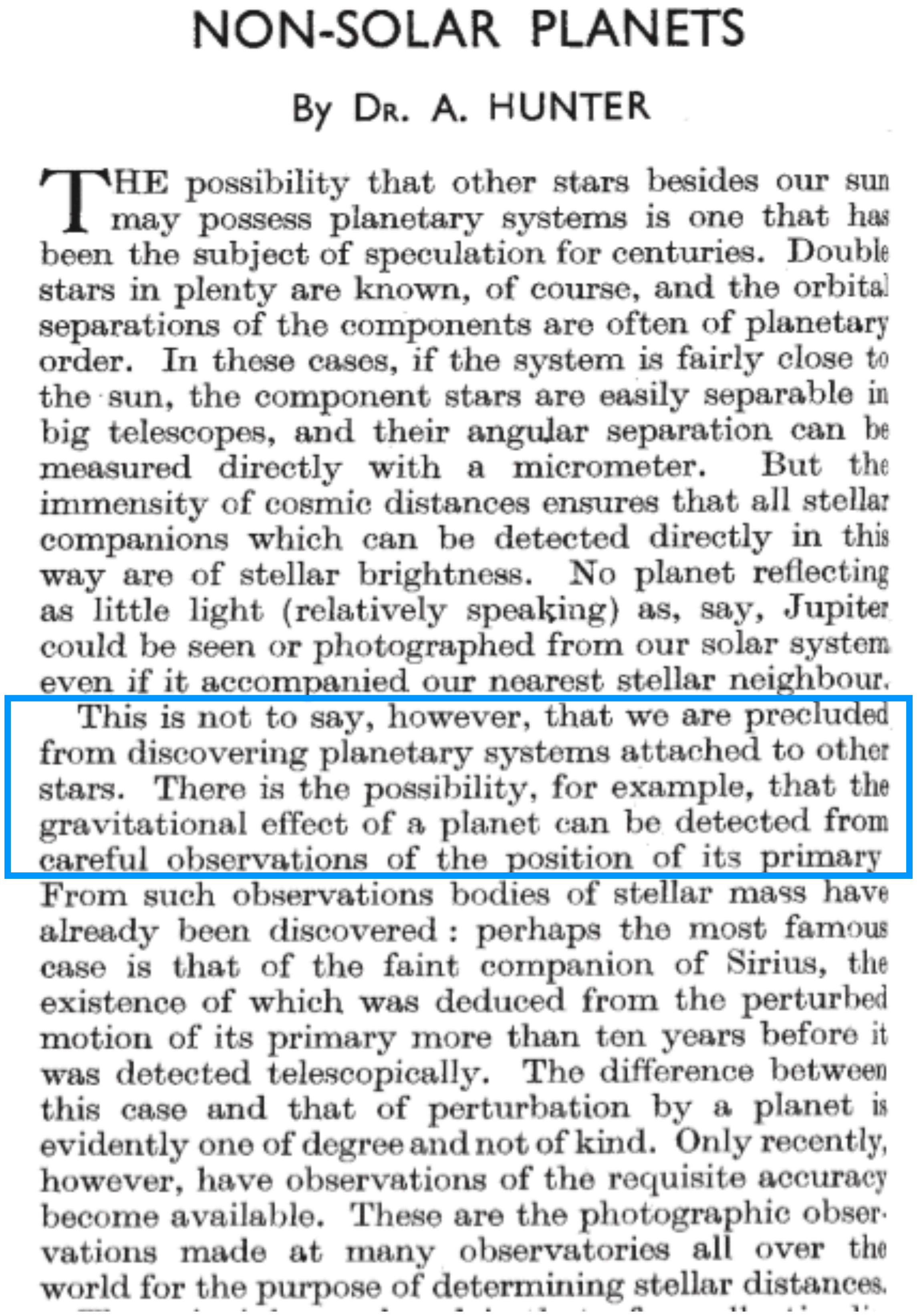
Extensive photographic observations of high accuracy taken at the Potsdam, Lick, and Sproul observatories have revealed perturbations in the orbital motion of 61 Cygni which are caused by a third, invisible member revolving around one of the two visual components.

The only solution which will satisfy the observed motions gives the remarkably small mass of 1/60 that of the sun or 16 times that of Jupiter. With a mass considerably smaller than the smallest known stellar mass (Krüger 60 $B = 0.14\odot$), the dark companion must have an intrinsic luminosity so extremely low that we may consider it a planet rather than a star. Thus planetary motion has been found outside the solar system.



“Exoplanet”
(sounds better)

Nature
(1943)



NON-SOLAR PLANETS

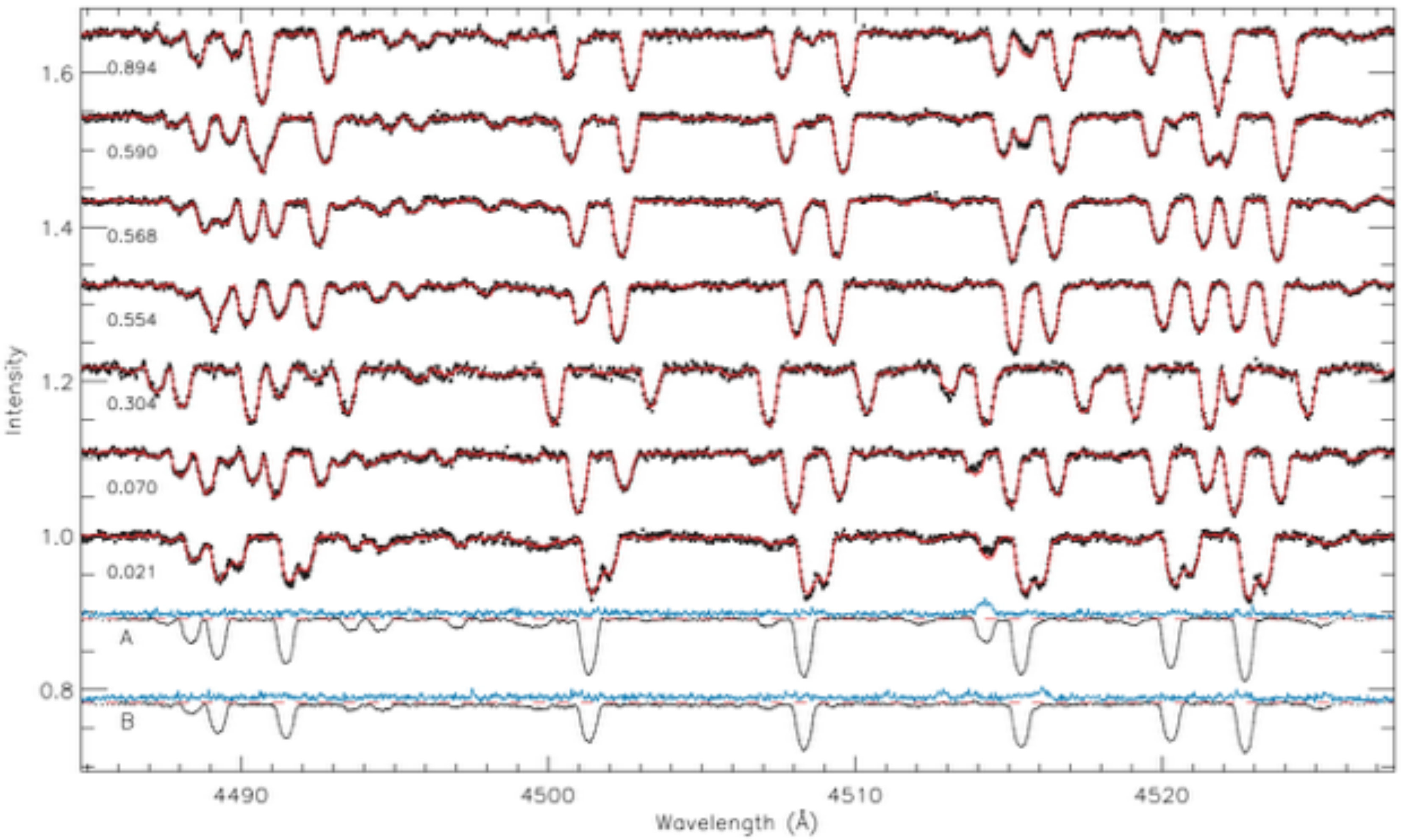
By Dr. A. HUNTER

THE possibility that other stars besides our sun may possess planetary systems is one that has been the subject of speculation for centuries. Double stars in plenty are known, of course, and the orbital separations of the components are often of planetary order. In these cases, if the system is fairly close to the sun, the component stars are easily separable in big telescopes, and their angular separation can be measured directly with a micrometer. But the immensity of cosmic distances ensures that all stellar companions which can be detected directly in this way are of stellar brightness. No planet reflecting as little light (relatively speaking) as, say, Jupiter could be seen or photographed from our solar system even if it accompanied our nearest stellar neighbour.

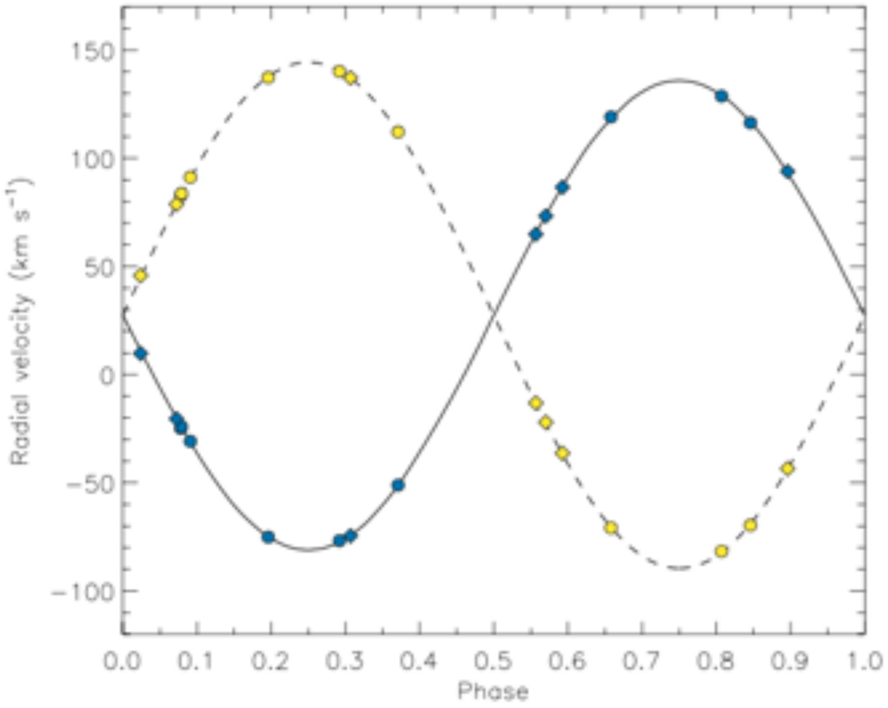
This is not to say, however, that we are precluded from discovering planetary systems attached to other stars. There is the possibility, for example, that the gravitational effect of a planet can be detected from careful observations of the position of its primary. From such observations bodies of stellar mass have already been discovered: perhaps the most famous case is that of the faint companion of Sirius, the existence of which was deduced from the perturbed motion of its primary more than ten years before it was detected telescopically. The difference between this case and that of perturbation by a planet is evidently one of degree and not of kind. Only recently, however, have observations of the requisite accuracy become available. These are the photographic observations made at many observatories all over the world for the purpose of determining stellar distances.

Spectroscopic Binaries

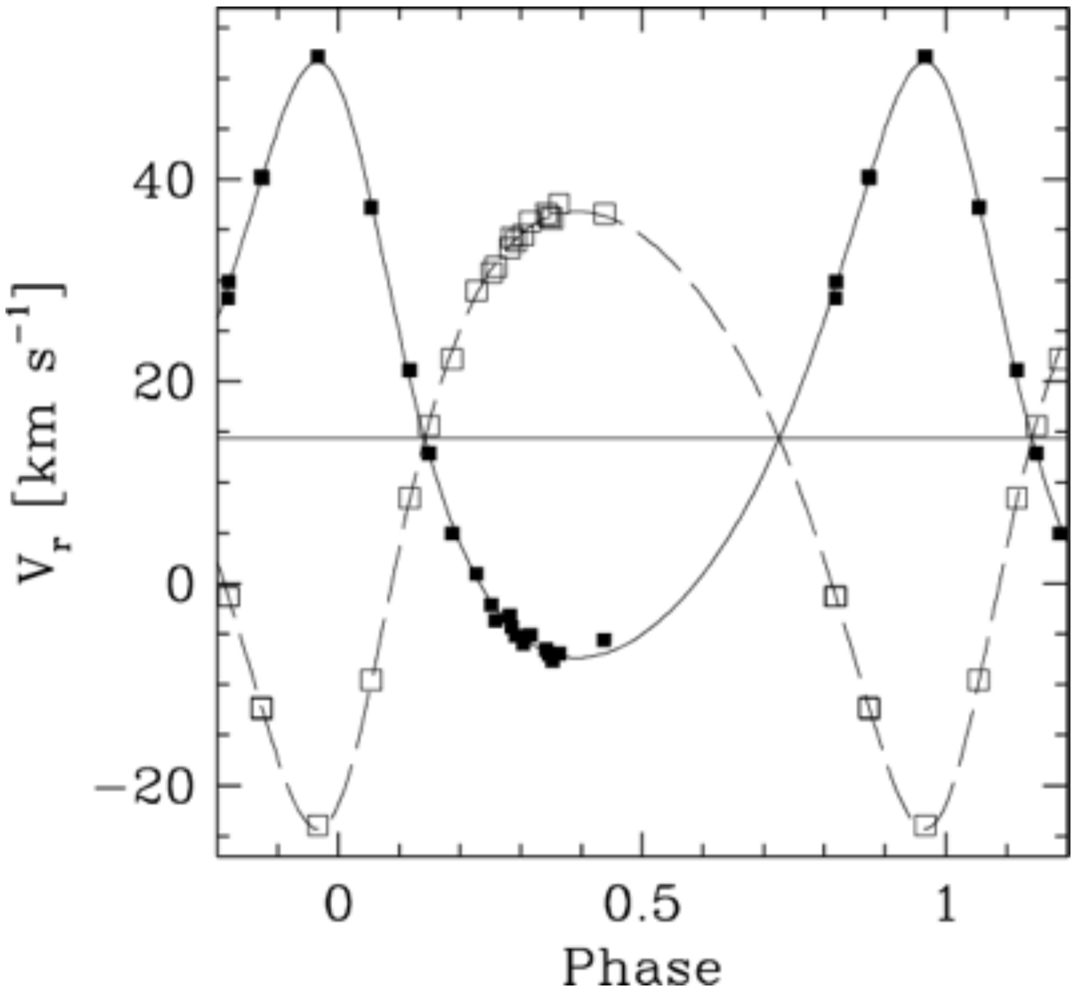
star: AR Aur



Folsom et al. 2010

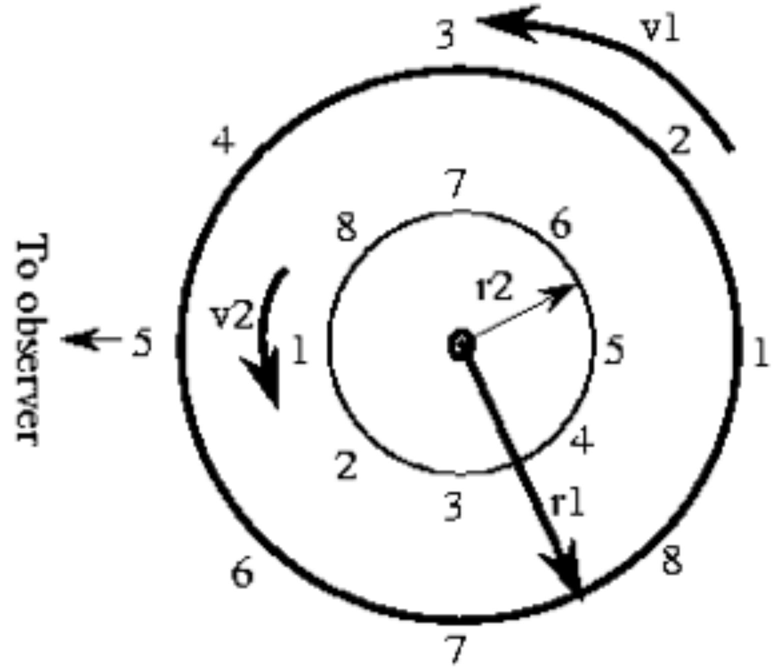


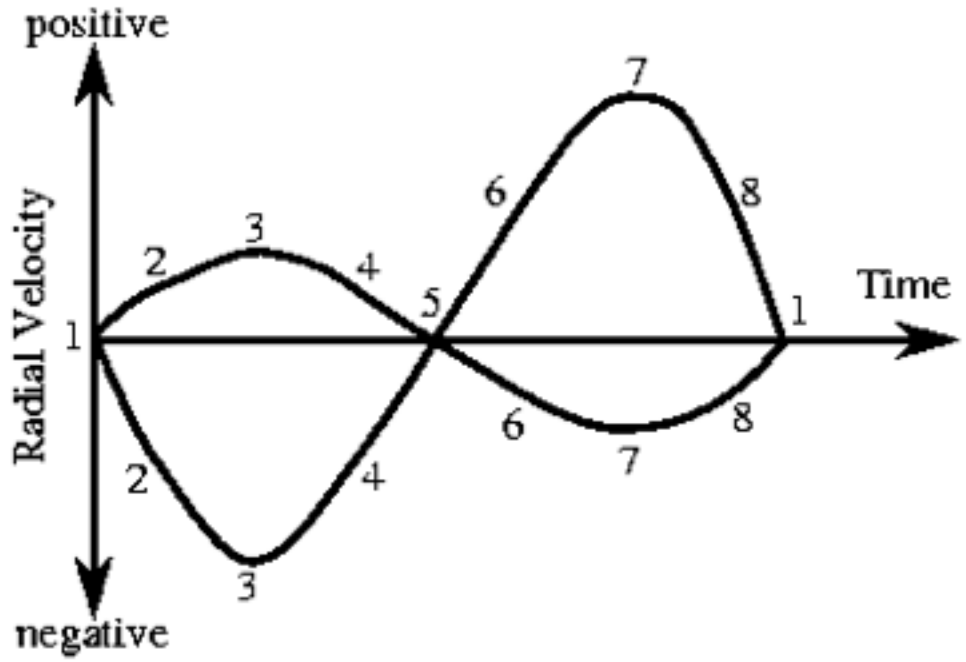
Spectroscopic Binaries



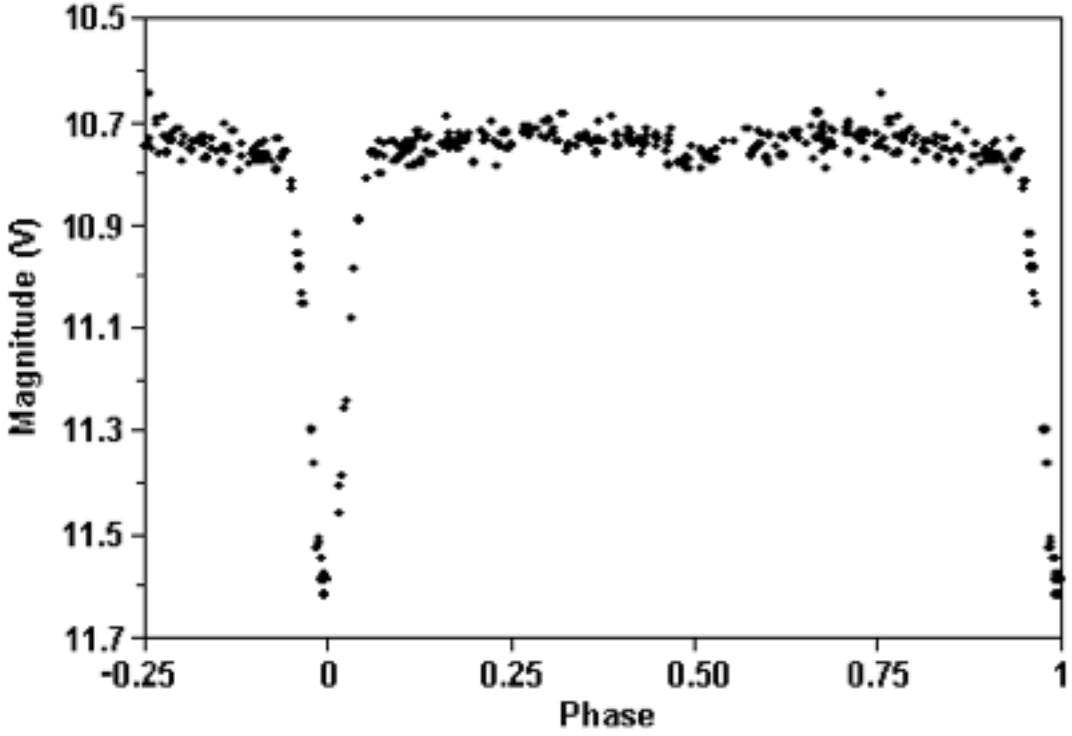
$$K \propto m_p \sin(i) P^{-1/3} M^{-2/3}$$

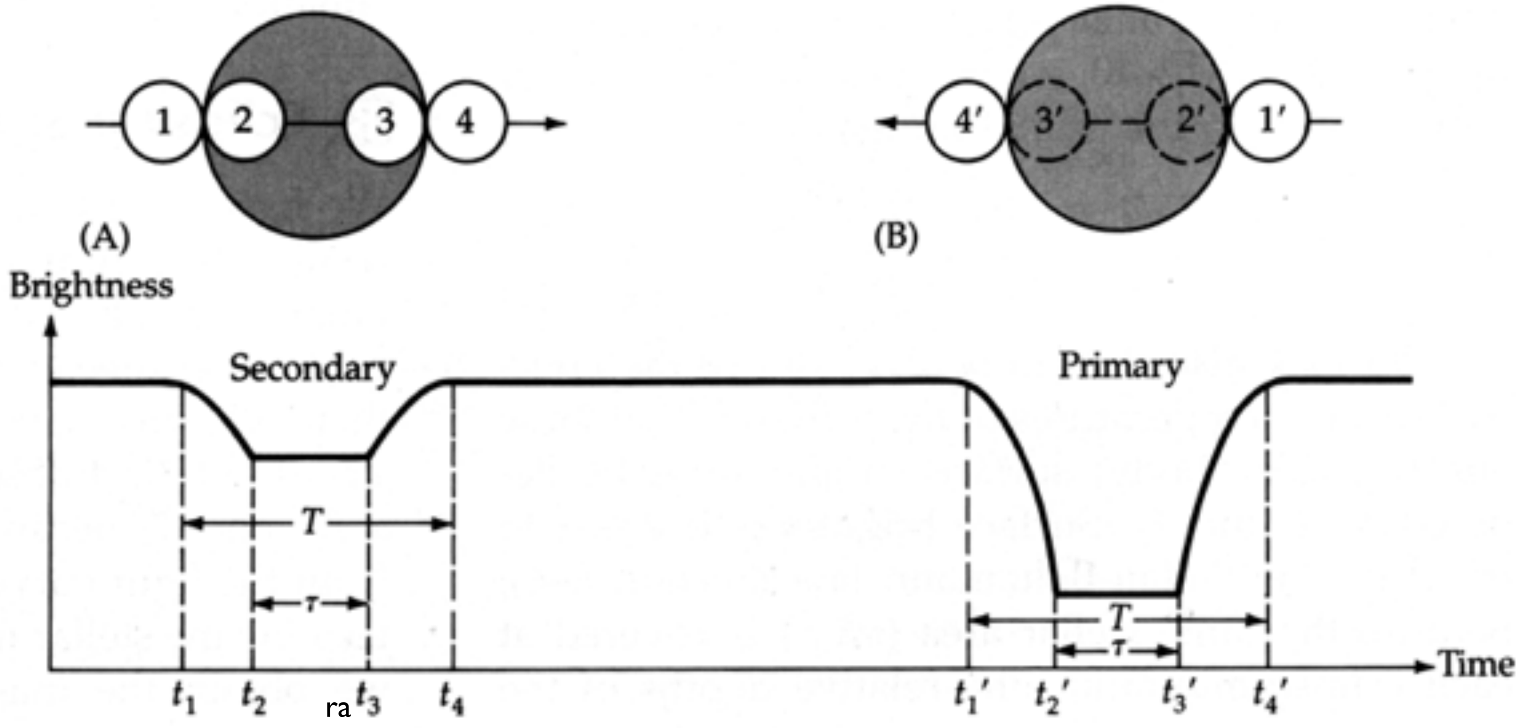
~ 10 m/s for Jupiter





Eclipsing Binaries



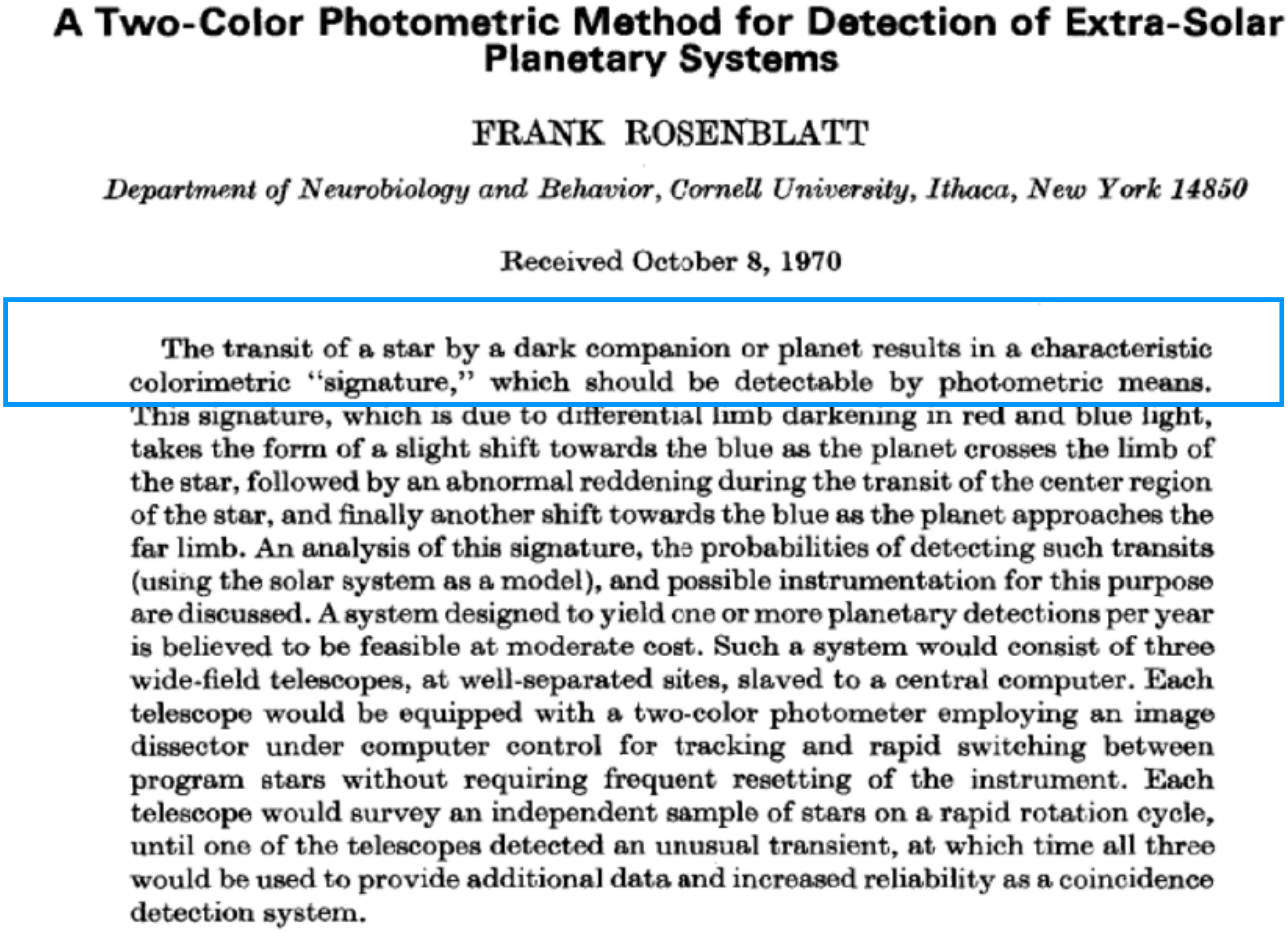


$$(\phi_3 - \phi_1) = (\phi_4 - \phi_2) = 2R_1/(2\pi a)$$

$$(\phi_2 - \phi_1) = (\phi_4 - \phi_3) = 2R_2/(2\pi a)$$

Many binaries known (a popular field for many decades) ... study masses, shapes, reflection, ...

See R. Matson 2016



A Two-Color Photometric Method for Detection of Extra-Solar Planetary Systems

FRANK ROSENBLATT

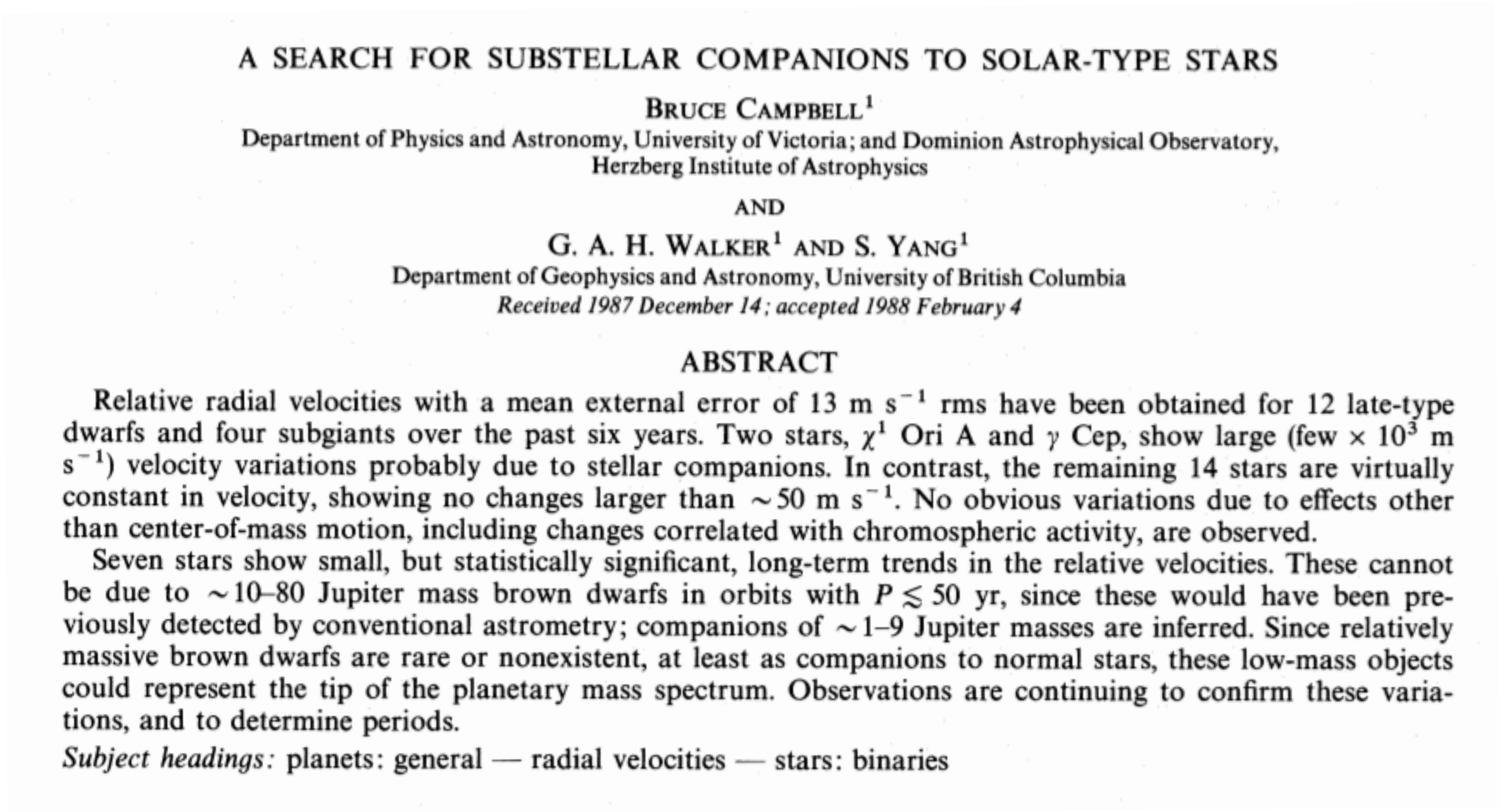
Department of Neurobiology and Behavior, Cornell University, Ithaca, New York 14850

Received October 8, 1970

The transit of a star by a dark companion or planet results in a characteristic colorimetric "signature," which should be detectable by photometric means. This signature, which is due to differential limb darkening in red and blue light, takes the form of a slight shift towards the blue as the planet crosses the limb of the star, followed by an abnormal reddening during the transit of the center region of the star, and finally another shift towards the blue as the planet approaches the far limb. An analysis of this signature, the probabilities of detecting such transits (using the solar system as a model), and possible instrumentation for this purpose are discussed. A system designed to yield one or more planetary detections per year is believed to be feasible at moderate cost. Such a system would consist of three wide-field telescopes, at well-separated sites, slaved to a central computer. Each telescope would be equipped with a two-color photometer employing an image dissector under computer control for tracking and rapid switching between program stars without requiring frequent resetting of the instrument. Each telescope would survey an independent sample of stars on a rapid rotation cycle, until one of the telescopes detected an unusual transient, at which time all three would be used to provide additional data and increased reliability as a coincidence detection system.

Also, Bill Borucki (Kepler PI) was thinking of ways to detected Earth-sized transits in late-70s / early-80s.

Almost the first Exoplanet (1988)



A SEARCH FOR SUBSTELLAR COMPANIONS TO SOLAR-TYPE STARS

BRUCE CAMPBELL[1]
Department of Physics and Astronomy, University of Victoria; and Dominion Astrophysical Observatory,
Herzberg Institute of Astrophysics

AND

G. A. H. WALKER[1] AND S. YANG[1]
Department of Geophysics and Astronomy, University of British Columbia
Received 1987 December 14; accepted 1988 February 4

ABSTRACT

Relative radial velocities with a mean external error of 13 m s^{-1} rms have been obtained for 12 late-type dwarfs and four subgiants over the past six years. Two stars, χ^1 Ori A and γ Cep, show large (few × 10^3 m s^{-1}) velocity variations probably due to stellar companions. In contrast, the remaining 14 stars are virtually constant in velocity, showing no changes larger than ~ 50 m s^{-1}. No obvious variations due to effects other than center-of-mass motion, including changes correlated with chromospheric activity, are observed.

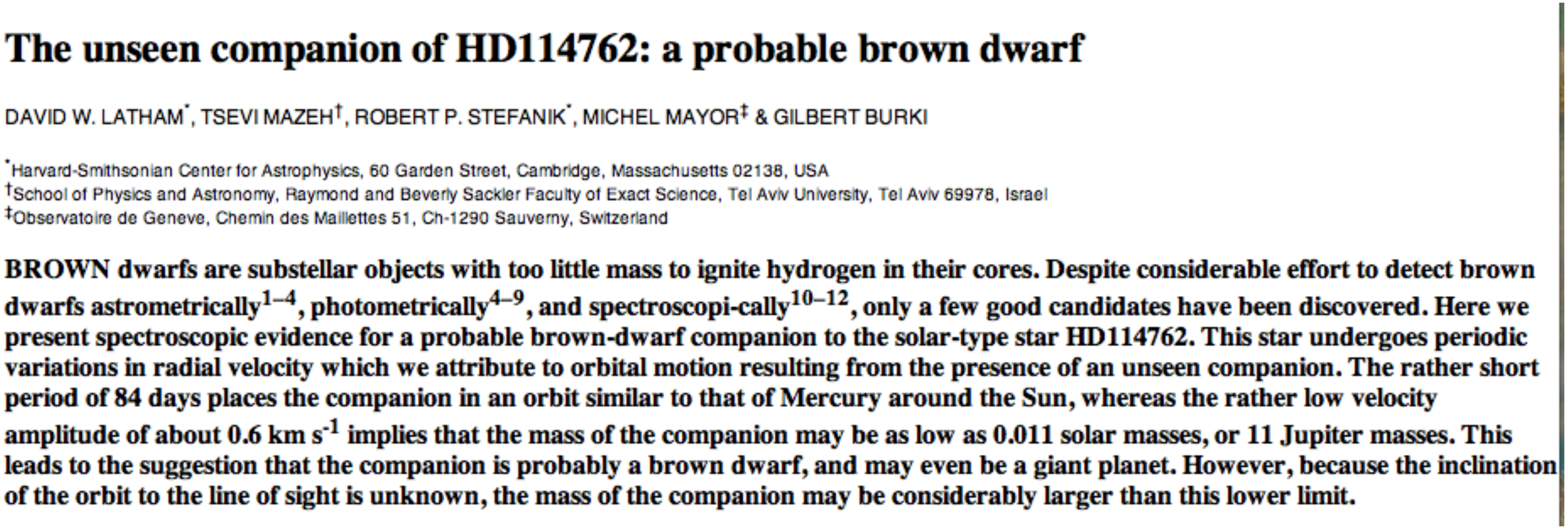
Seven stars show small, but statistically significant, long-term trends in the relative velocities. These cannot be due to ~ 10–80 Jupiter mass brown dwarfs in orbits with $P \lesssim 50$ yr, since these would have been previously detected by conventional astrometry; companions of ~ 1–9 Jupiter masses are inferred. Since relatively massive brown dwarfs are rare or nonexistent, at least as companions to normal stars, these low-mass objects could represent the tip of the planetary mass spectrum. Observations are continuing to confirm these variations, and to determine periods.

Subject headings: planets: general — radial velocities — stars: binaries

(Initially believed to be stellar activity,
planet around gam Cep confirmed in 2002/3)

see cochran et al. 2002 and hatzes et al. 2003

Almost the first Exoplanet (1989)
(RV measurement)



The unseen companion of HD114762: a probable brown dwarf

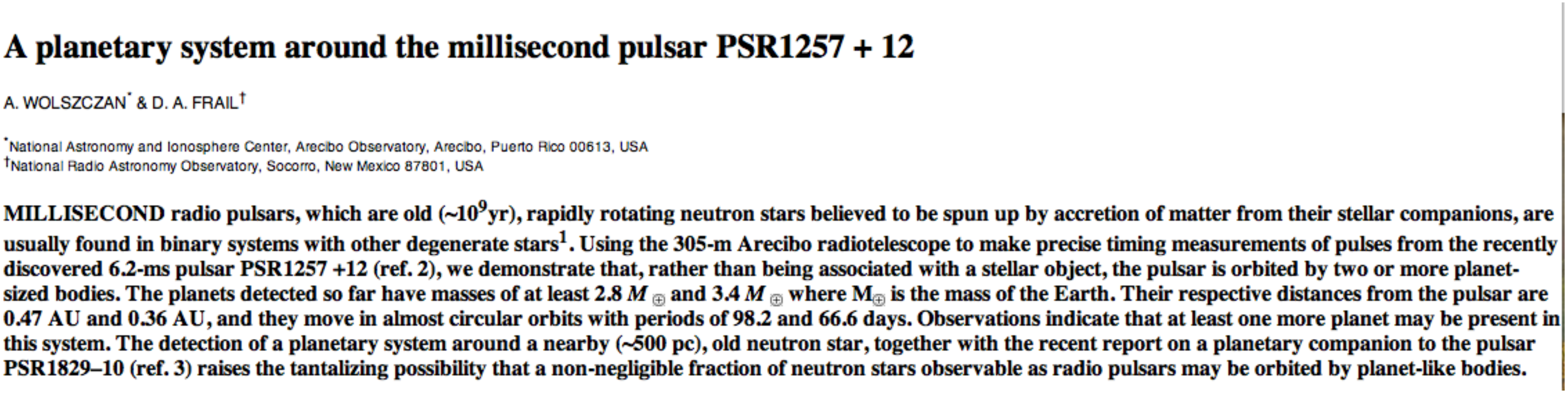
DAVID W. LATHAM[*], TSEVI MAZEH[†], ROBERT P. STEFANIK[*], MICHEL MAYOR[‡] & GILBERT BURKI

[*]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA
[†]School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Science, Tel Aviv University, Tel Aviv 69978, Israel
[‡]Observatoire de Geneve, Chemin des Maillettes 51, Ch-1290 Sauverny, Switzerland

BROWN dwarfs are substellar objects with too little mass to ignite hydrogen in their cores. Despite considerable effort to detect brown dwarfs astrometrically[1–4], photometrically[4–9], and spectroscopi-cally[10–12], only a few good candidates have been discovered. Here we present spectroscopic evidence for a probable brown-dwarf companion to the solar-type star HD114762. This star undergoes periodic variations in radial velocity which we attribute to orbital motion resulting from the presence of an unseen companion. The rather short period of 84 days places the companion in an orbit similar to that of Mercury around the Sun, whereas the rather low velocity amplitude of about 0.6 km s^{-1} implies that the mass of the companion may be as low as 0.011 solar masses, or 11 Jupiter masses. This leads to the suggestion that the companion is probably a brown dwarf, and may even be a giant planet. However, because the inclination of the orbit to the line of sight is unknown, the mass of the companion may be considerably larger than this lower limit.

sin(i) ambiguity suggested mass in the brown dwarf regime (~ 13 to 75 Jupiter-mass)

Planet-mass companions (1992)
two, ~ 3 Earth-mass, planets orbiting stellar remnant.



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 (~10^9yr), 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.

(also has inner, 3rd planet!)

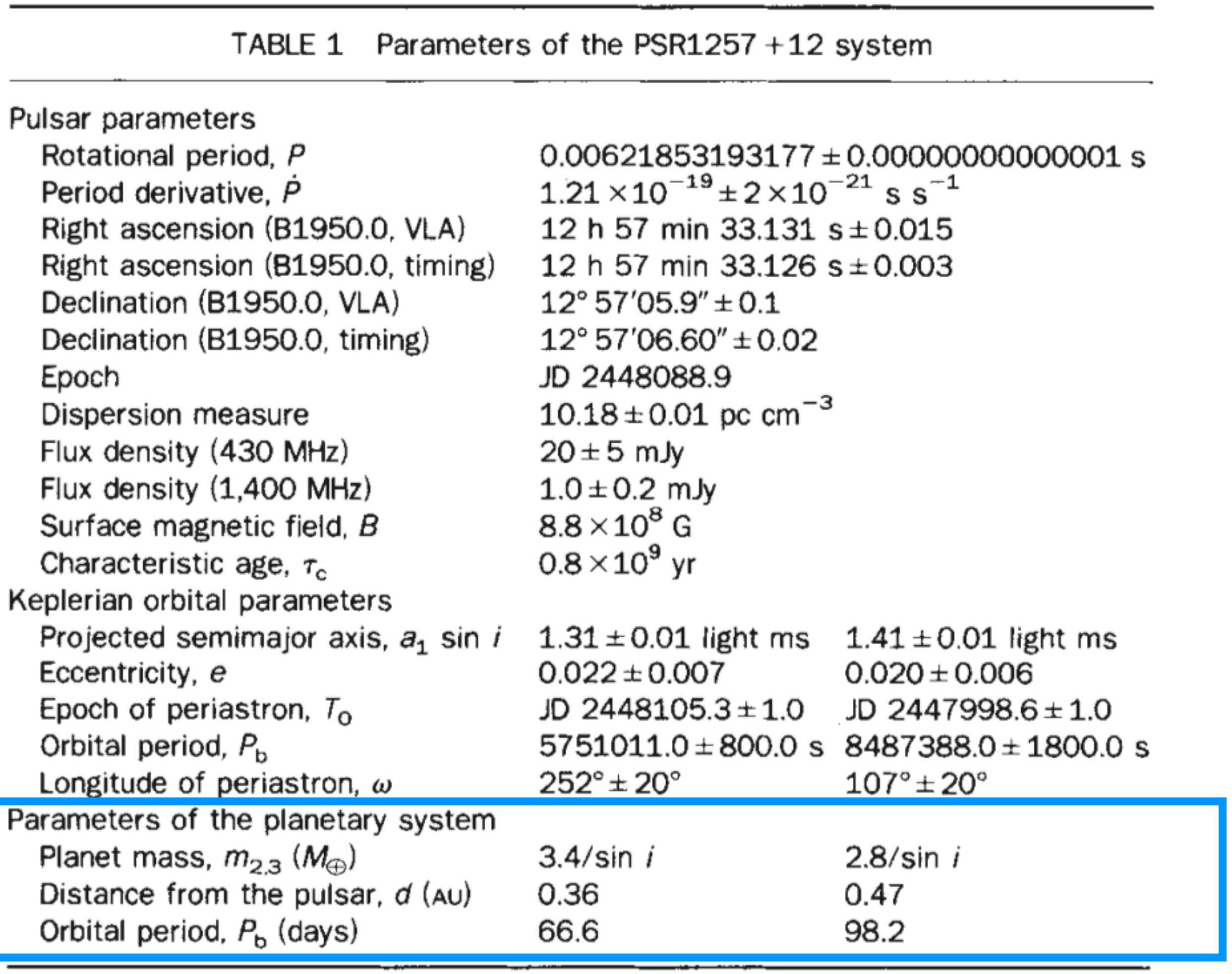
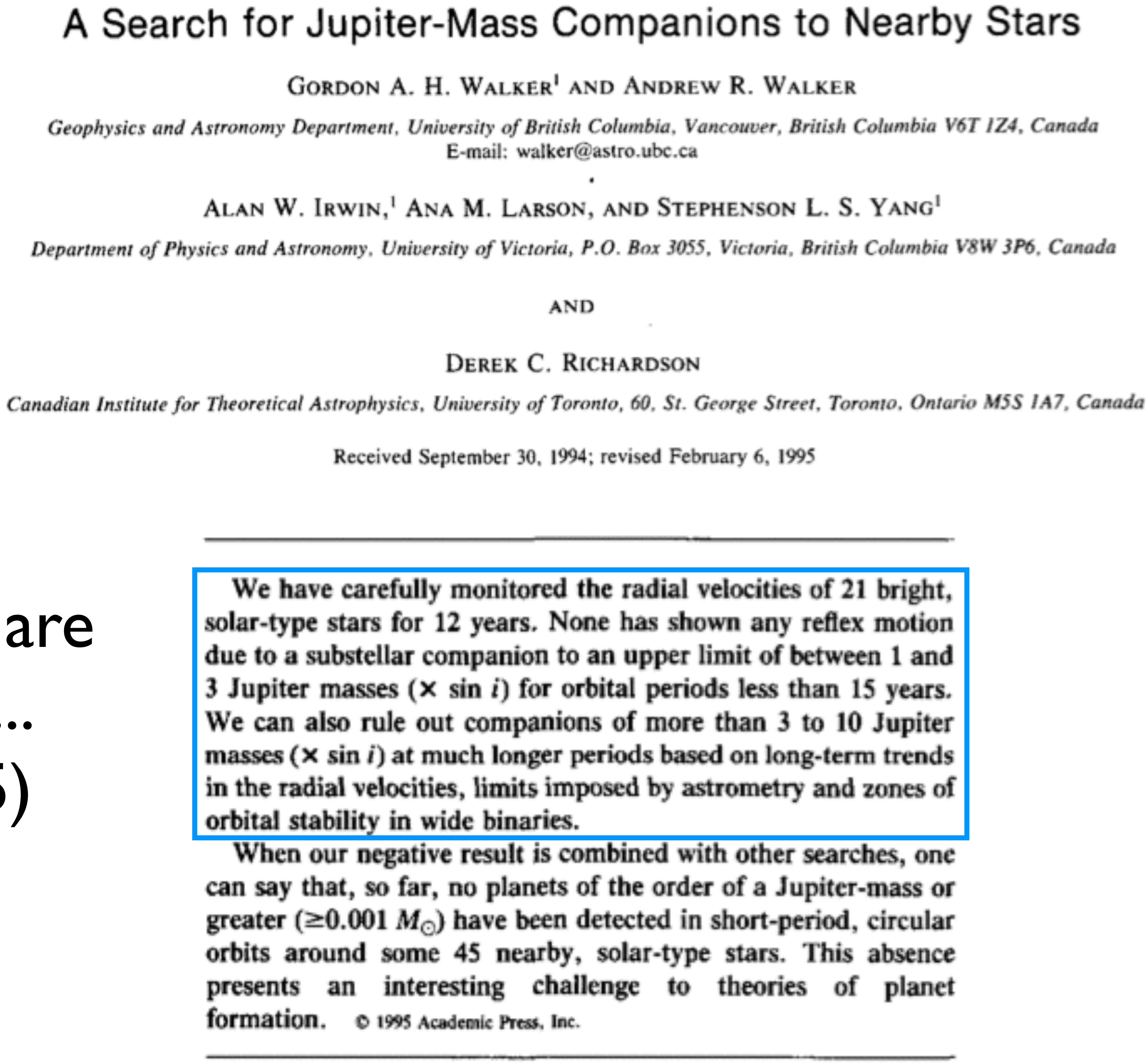


TABLE 1 Parameters of the PSR1257 +12 system

Pulsar parameters		
Rotational period, P	0.00621853193177 ± 0.00000000000001 s	
Period derivative, $\dot{P}$	$1.21\times10^{-19}\pm2\times10^{-21}$ s s^{-1}	
Right ascension (B1950.0, VLA)	12 h 57 min 33.131 s ± 0.015	
Right ascension (B1950.0, timing)	12 h 57 min 33.126 s ± 0.003	
Declination (B1950.0, VLA)	12° 57′05.9″ ± 0.1	
Declination (B1950.0, timing)	12° 57′06.60″ ± 0.02	
Epoch	JD 2448088.9	
Dispersion measure	10.18 ± 0.01 pc cm^{-3}	
Flux density (430 MHz)	20 ± 5 mJy	
Flux density (1,400 MHz)	1.0 ± 0.2 mJy	
Surface magnetic field, B	8.8×10^8 G	
Characteristic age, τ_c	0.8×10^9 yr	
Keplerian orbital parameters		
Projected semimajor axis, a_1 sin i	1.31 ± 0.01 light ms	1.41 ± 0.01 light ms
Eccentricity, e	0.022 ± 0.007	0.020 ± 0.006
Epoch of periastron, T_0	JD 2448105.3 ± 1.0	JD 2447998.6 ± 1.0
Orbital period, P_b	5751011.0 ± 800.0 s	8487388.0 ± 1800.0 s
Longitude of periastron, ω	252° ± 20°	107° ± 20°
Parameters of the planetary system		
Planet mass, $m_{2,3}$ ($M_\oplus$)	3.4/sin i	2.8/sin i
Distance from the pulsar, d (AU)	0.36	0.47
Orbital period, P_b (days)	66.6	98.2

Planets are rare ... (1995)



A Search for Jupiter-Mass Companions to Nearby Stars

Gordon A. H. Walker[1] and Andrew R. Walker

Geophysics and Astronomy Department, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada
E-mail: walker@astro.ubc.ca

Alan W. Irwin,[1] Ana M. Larson, and Stephenson L. S. Yang[1]

Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, Victoria, British Columbia V8W 3P6, Canada

and

Derek C. Richardson

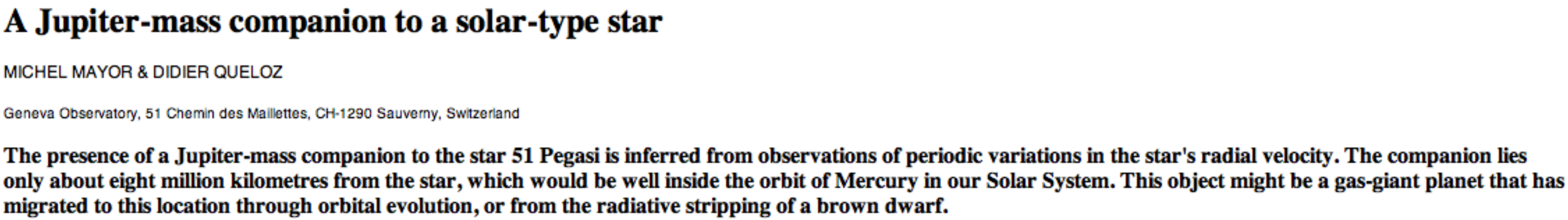
Canadian Institute for Theoretical Astrophysics, University of Toronto, 60, St. George Street, Toronto, Ontario M5S 1A7, Canada

Received September 30, 1994; revised February 6, 1995

We have carefully monitored the radial velocities of 21 bright, solar-type stars for 12 years. None has shown any reflex motion due to a substellar companion to an upper limit of between 1 and 3 Jupiter masses (× sin *i*) for orbital periods less than 15 years. We can also rule out companions of more than 3 to 10 Jupiter masses (× sin *i*) at much longer periods based on long-term trends in the radial velocities, limits imposed by astrometry and zones of orbital stability in wide binaries.

When our negative result is combined with other searches, one can say that, so far, no planets of the order of a Jupiter-mass or greater ($\geq 0.001\ M_\odot$) have been detected in short-period, circular orbits around some 45 nearby, solar-type stars. This absence presents an interesting challenge to theories of planet formation.

51 Peg (1995/96)

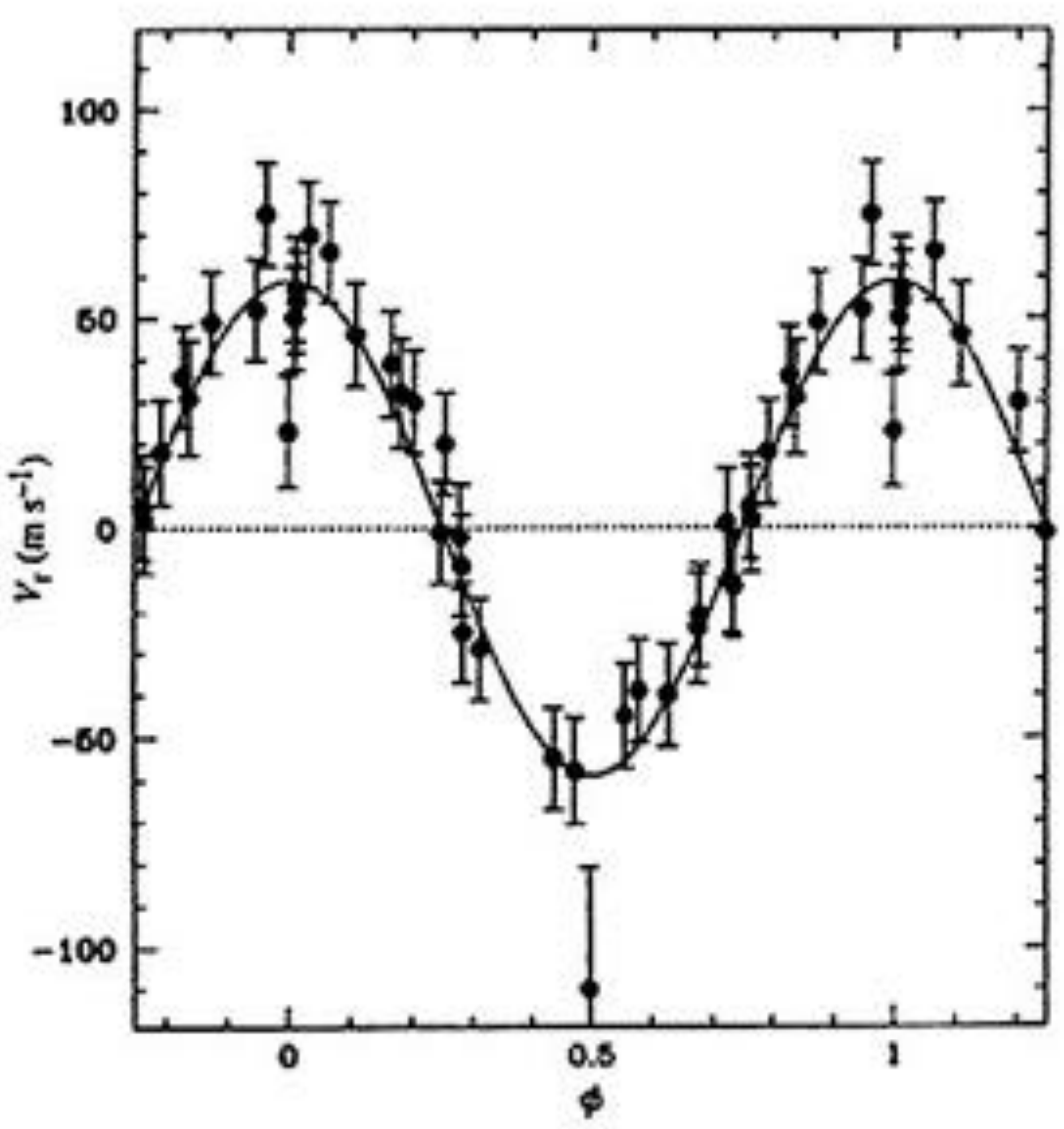


A Jupiter-mass companion to a solar-type star

MICHEL MAYOR & DIDIER QUELOZ

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

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.



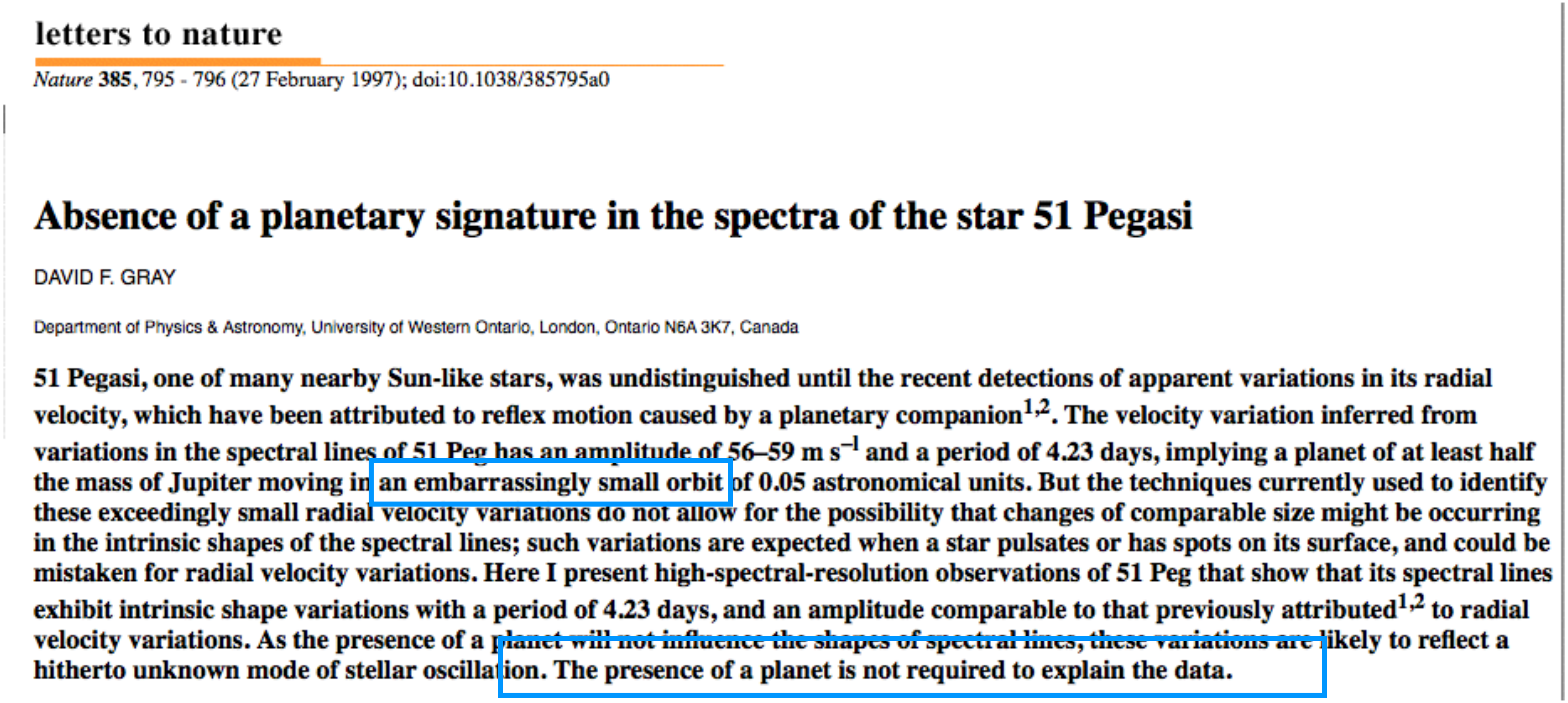
P = 4.2 days

Mp sin(i) = 0.5 Mjup

orbits “normal” sun-like star

There were many skeptics!

Most significant challenge came from David Gray:



letters to nature

Nature **385**, 795 - 796 (27 February 1997); doi:10.1038/385795a0

Absence of a planetary signature in the spectra of the star 51 Pegasi

DAVID F. GRAY

Department of Physics & Astronomy, University of Western Ontario, London, Ontario N6A 3K7, Canada

51 Pegasi, one of many nearby Sun-like stars, was undistinguished until the recent detections of apparent variations in its radial velocity, which have been attributed to reflex motion caused by a planetary companion[1,2]. The velocity variation inferred from variations in the spectral lines of 51 Peg has an amplitude of 56–59 $\mathrm{m\ s^{-1}}$ and a period of 4.23 days, implying a planet of at least half the mass of Jupiter moving in an embarrassingly small orbit of 0.05 astronomical units. But the techniques currently used to identify these exceedingly small radial velocity variations do not allow for the possibility that changes of comparable size might be occurring in the intrinsic shapes of the spectral lines; such variations are expected when a star pulsates or has spots on its surface, and could be mistaken for radial velocity variations. Here I present high-spectral-resolution observations of 51 Peg that show that its spectral lines exhibit intrinsic shape variations with a period of 4.23 days, and an amplitude comparable to that previously attributed[1,2] to radial velocity variations. As the presence of a planet will not influence the shapes of spectral lines, these variations are likely to reflect a hitherto unknown mode of stellar oscillation. The presence of a planet is not required to explain the data.

Line-bisector analysis

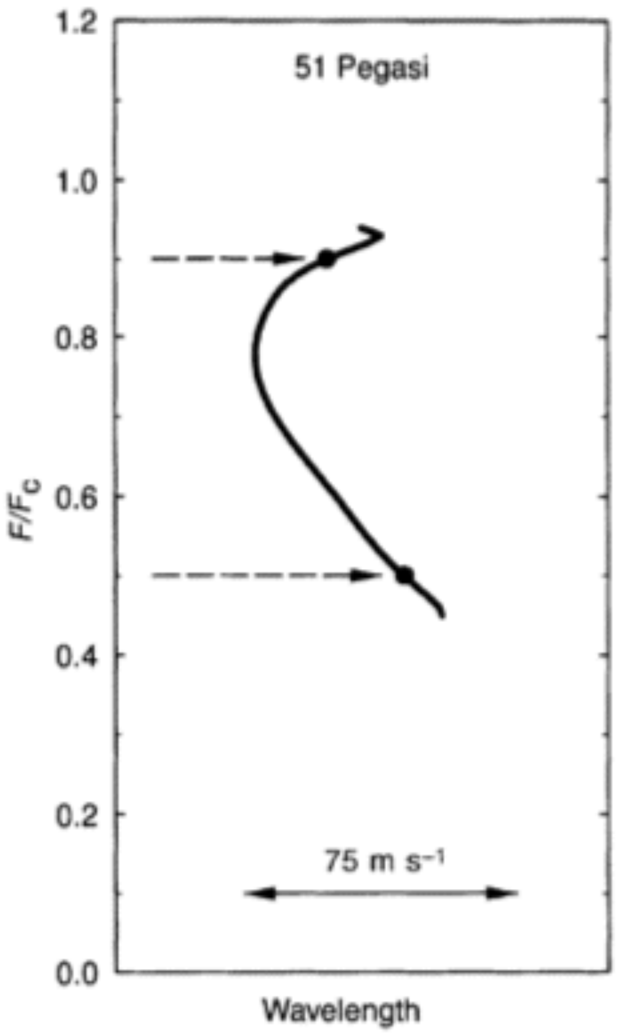
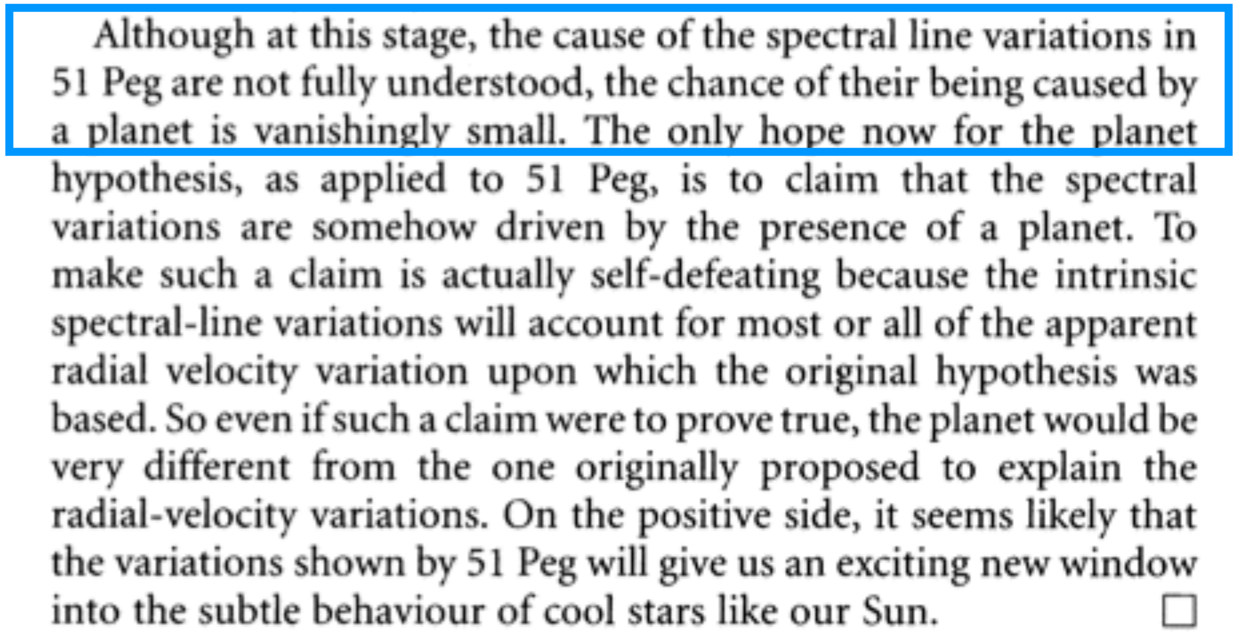
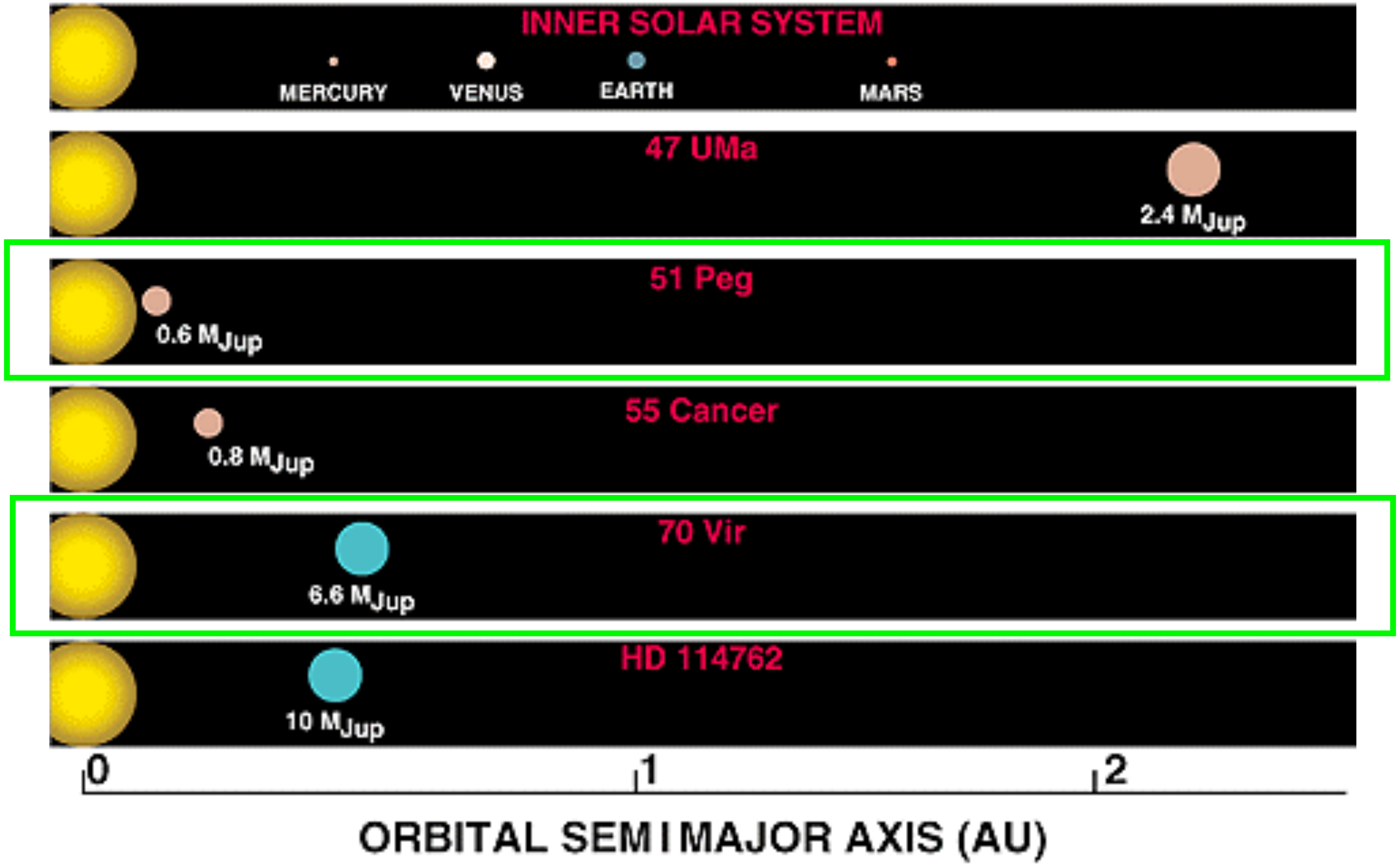


Figure 1 The average of 39 exposures of the line bisector of Fe I 6,253 Å. The plot of F/F_c, flux normalized to the continuum, against wavelength displays the typical 'C' shape induced by granulation on the surface of the star. Hot convective cells rise, giving to their light a net Doppler shift to the blue (integrated over the hemisphere of the star facing us), while cooled material returns downward, giving a net Doppler shift to the red. As the fraction of light coming from the hot material is substantially larger than the light from the cooled material, the combined effect is an asymmetrical broadening of the spectral lines. The wavelength difference, expressed in velocity units, between the two indicated points is the velocity span used to parametrize the cyclic variations in the upper panels of Fig. 2.



Although at this stage, the cause of the spectral line variations in 51 Peg are not fully understood, the chance of their being caused by a planet is vanishingly small. The only hope now for the planet hypothesis, as applied to 51 Peg, is to claim that the spectral variations are somehow driven by the presence of a planet. To make such a claim is actually self-defeating because the intrinsic spectral-line variations will account for most or all of the apparent radial velocity variation upon which the original hypothesis was based. So even if such a claim were to prove true, the planet would be very different from the one originally proposed to explain the radial-velocity variations. On the positive side, it seems likely that the variations shown by 51 Peg will give us an exciting new window into the subtle behaviour of cool stars like our Sun. ☐

More RV signals found indicating 51-Peg b was not alone.

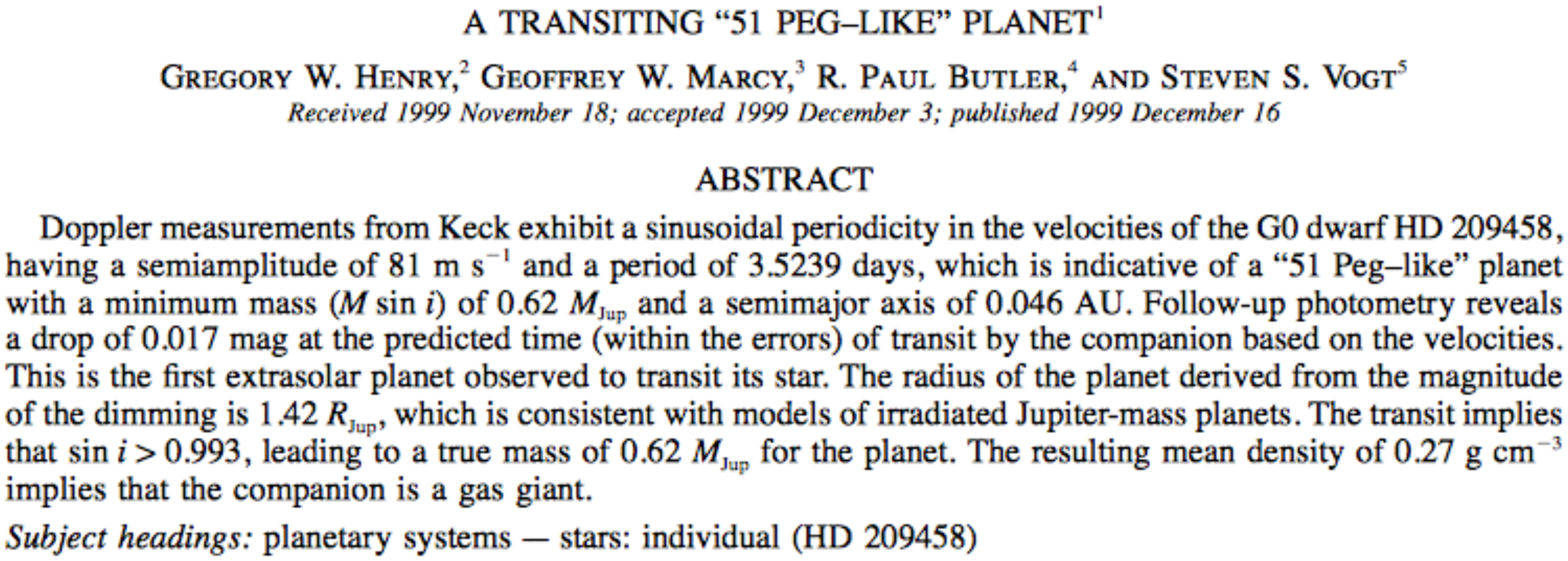


1st RV planet

1995

2nd RV planet

1996



A TRANSITING "51 PEG–LIKE" PLANET[1]

GREGORY W. HENRY,[2] GEOFFREY W. MARCY,[3] R. PAUL BUTLER,[4] AND STEVEN S. VOGT[5]

Received 1999 November 18; accepted 1999 December 3; published 1999 December 16

ABSTRACT

Doppler measurements from Keck exhibit a sinusoidal periodicity in the velocities of the G0 dwarf HD 209458, having a semiamplitude of 81 m s^{-1} and a period of 3.5239 days, which is indicative of a "51 Peg–like" planet with a minimum mass ($M \sin i$) of 0.62 $M_{\rm Jup}$ and a semimajor axis of 0.046 AU. Follow-up photometry reveals a drop of 0.017 mag at the predicted time (within the errors) of transit by the companion based on the velocities. This is the first extrasolar planet observed to transit its star. The radius of the planet derived from the magnitude of the dimming is 1.42 $R_{\rm Jup}$, which is consistent with models of irradiated Jupiter-mass planets. The transit implies that $\sin i > 0.993$, leading to a true mass of 0.62 $M_{\rm Jup}$ for the planet. The resulting mean density of 0.27 g cm^{-3} implies that the companion is a gas giant.

Subject headings: planetary systems — stars: individual (HD 209458)

HD209458b found by Keck Doppler survey 1st, transit detected in 1999.

partial transit

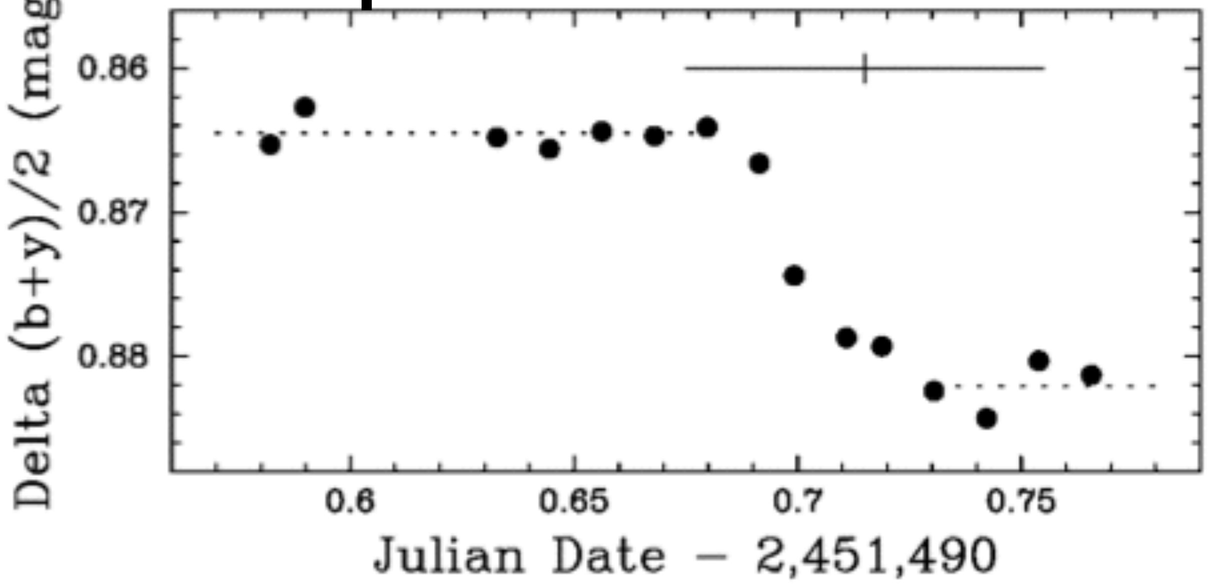


FIG. 3.—Photometric observations of HD 209458 from the night of 1999 November 7 UT showing ingress of the planetary transit. The measured transit depth is 0.017 ± 0.002 mag or 1.58% ± 0.18%. The error bar shows the time of inferior conjunction and its uncertainty predicted from the radial velocities in this Letter.

(see also Charbonneau et al. 2000)

The discovery of *transiting* “51 Peg-Like” Planets, erased previous doubts about planets in “embarrassingly small” orbits.

The race was on to discovery more and characterize their properties ....

Meanwhile, next door (in mass)

- The first T-type (methane absorption in spectrum) brown dwarf, Gl299B, was discovered (Nakajima et al. 1995).

- In the late 90's and early 2000's, brown dwarf discoveries were growing in number (initially outpacing exoplanets) from all-sky near-IR surveys.

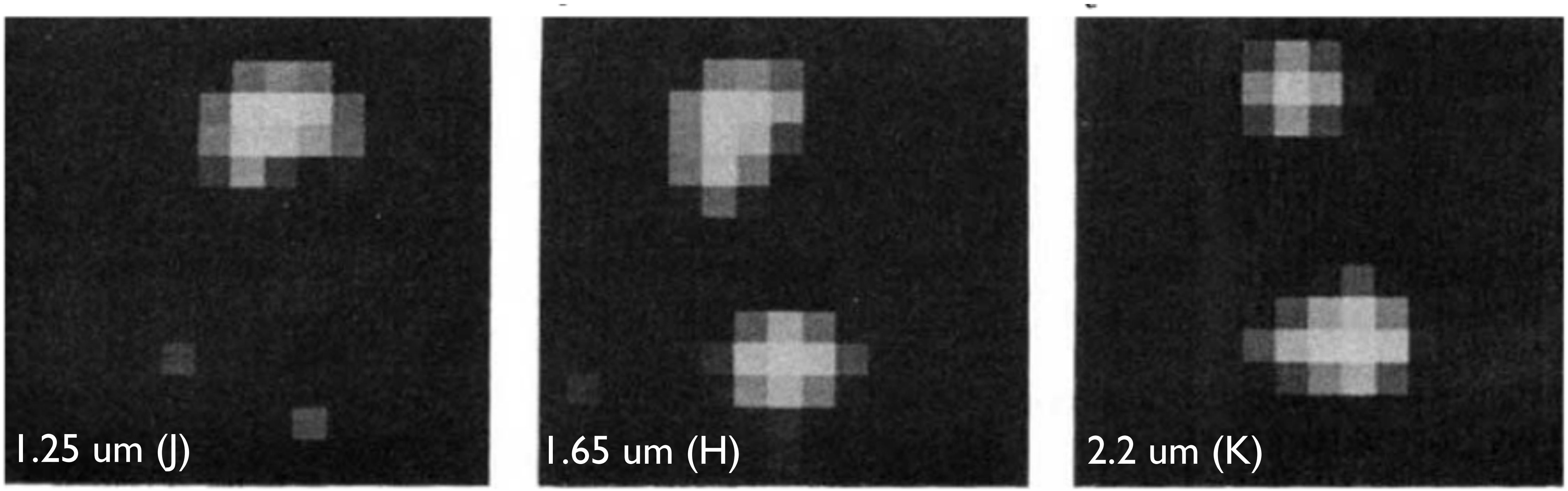
- The near-simultaneous discovery of BDs and massive EGPs, fueled the (often heated) debate over where to draw the line in mass, between a "real" planet and brown dwarf.

Meanwhile, next door (in mass)

Early "direct imaging" results:

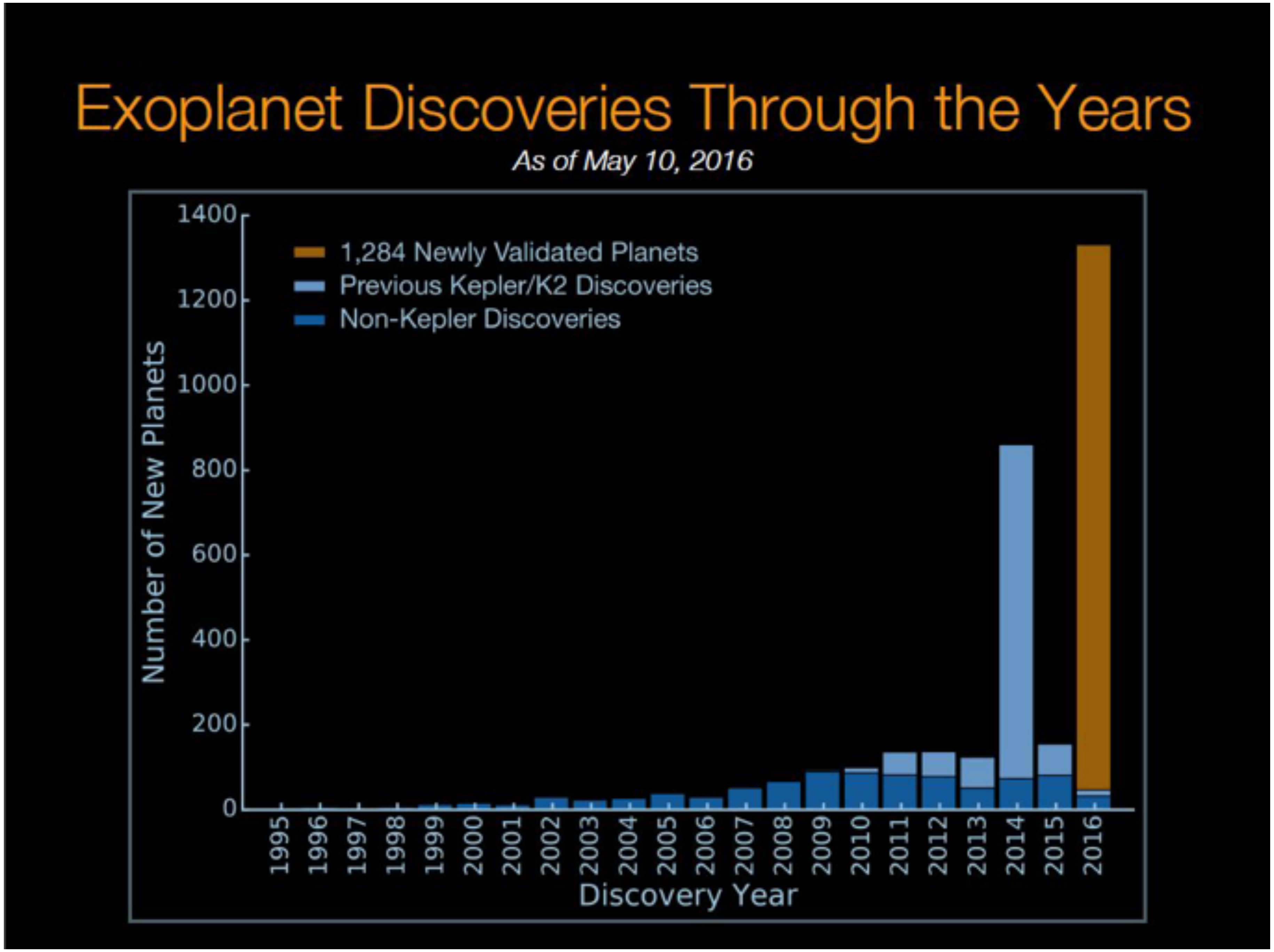
GD165AB (brown dwarf + white dwarf)

(Becklin & Zuckerman 1988)



~ 7 arcsec

51 Peg b is often called the first, but several other exoplanets were essentially contemporaneous discoveries.



A lot has happened since 1995 ...

(notice that RV yield started to decrease in 2011)

- RV surveys continue today, several with 1m/s precision (looking for longer period planets and augmenting transit surveys)

- Kepler has found > 3000 candidates, of which < 10% are false positives.

- Direct Imaging, astrometry, micro-lensing remain minority players in discoveries, but still play important roles.

Reading list ...

- Fischer et al. chapter in *PPVI*, *Exoplanet Detection Techniques*
- Chapter 2 in *Exoplanets* (Fischer & Lovis) pg 27 - 53.
- Science 2013 special issue on exoplanets, Howard et al., *Observed Properties of Extrasolar Planets*
- Nature 2014, Lissauer et al., *Advances in exoplanet science from Kepler*