Prelude to, and Nature of the Space Photometry Revolution

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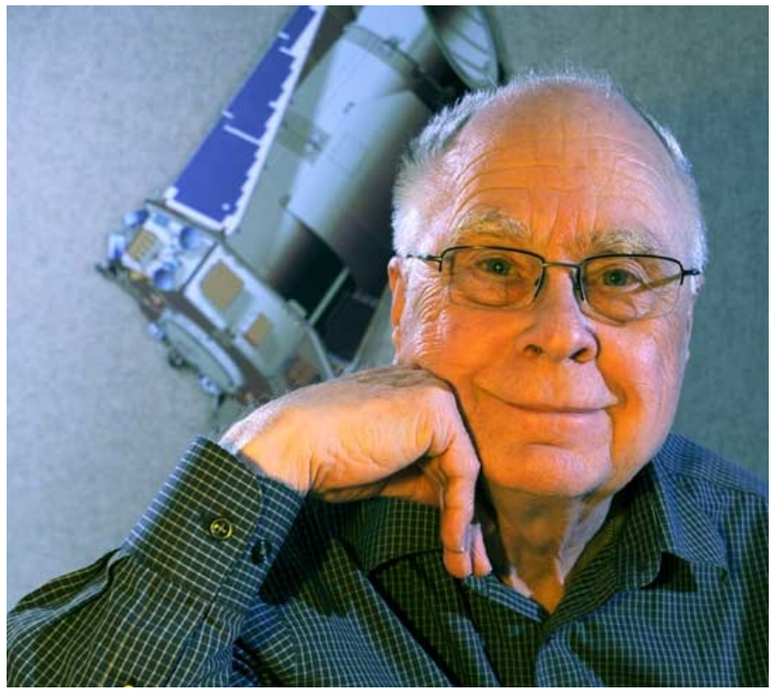


Bill Borucki

Thanks to:

Tim Brown

Bill Borucki, Dave Koch, Jon Jenkins

Jørgen C.-D., Hans Kjeldsen

Bill Chaplin

Definitions and Characteristics of Revolutions:

Dictionary:

- a forcible overthrow of a government or social order in favor of a new system
- a dramatic and wide-ranging change in the way something works or is organized or in people's ideas about it

Vladimir Lenin:

- A revolution is impossible without a revolutionary situation.
- It is impossible to predict the time and progress of revolution. It is governed by its own more or less mysterious laws.

Surely the workings of ESA and NASA qualify as mysterious, at best — in an alternate Universe . . .

The Space Photometry Revolution

MONS Symposium 3, Eddington EASC-7 joint meeting

Prelude to, and Nature of the Space Photometry Revolution

Ian Roxburgh, Queen Mary University of London

But, as you know Eddington (figuratively) went up in smoke.

You're stuck with me.

Prelude to the revolution: the situation in 1994.

Why 1994?

- nice round number of 20 years
- no significant results yet for exoplanets or asteroseismology
- ARAA article “Asteroseismology” by Tim Brown and myself
- GONG ’94: Helio- and Astero-seismology From the Earth and Space (Ulrich, Rhodes, Däppen)
- Astrophysical Science with a Spaceborne Photometric Telescope (Borucki/FRESIP)
- COROT proposed as concept to CNES with Claude Catala as PI.
- FRESIP (Kepler) proposed to NASA Discovery Mission.

Lot’s of earlier activity:

Beginnings of Asteroseismolgy
Douglas Gough, Nature 1985

- refers to separate French and American papers in 1984 claiming detections on other stars

Progress over 1995-1999

- **51 Peg b!** Mayor and Queloz, followed quickly by confirmation by Marcy and Butler, and more detections by both groups.
- Nay-sayers still were listened to, e.g., David Black contended that none of these were likely exoplanets.
- **Transits on HD 209458!** The exoplanet skeptics were silenced.

No usable asteroseismology successes, despite several groups really trying. Efforts to advocate for a space mission intensify.

Bedding and Kjeldsen
Kjeldsen and Bedding

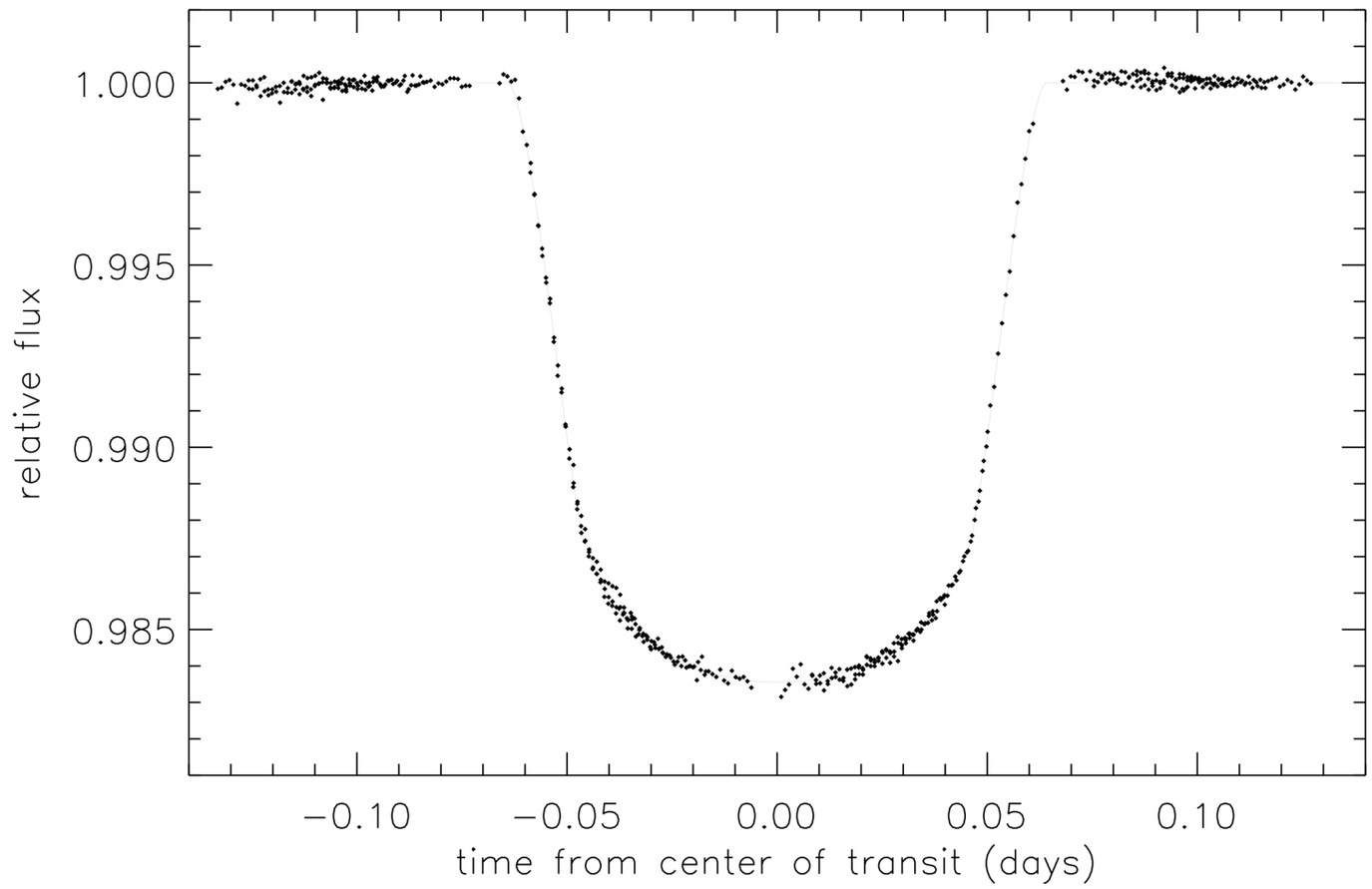
Start annual, or more frequent chronicles of ground-based progress

Space photometry — Cosmology — Two groups publish evidence for an accelerating Universe making use of HST photometry — a revolution.

Progress over 2000-2004.

HST photometric, spectroscopic observations of HD 209458 b transit. Brown, et al. 2001.

Such a light curve now routine, wasn't then.



Pace of RV-based exoplanet detections continues to accelerate.

Asteroseismology: Success!!! Francois Bouchy and Fabien Carrier — α Cen A — robust, obvious, supports interpretations, 2001.
Søren Frandsen — ξ Hya, Tim Bedding — β Hyi, Hans Kjeldsen — η Boo.

Multiple missions selected, dropped, etc.
Kepler and COROT were selected, and kept!

How KASC came to be.

Asteroseismology by the Kepler Science Team (by Tim Brown and myself) was an integral part of the Kepler Mission proposal to, and acceptance by NASA. Price to NASA: $750,000, mainly for six years postdoc support over the full mission.

Tim and I always recognized we were under supported, and by 2003 were talking in a relaxed way to Jørgen about helping out with theory/ interpretations. Jørgen very involved with our competitor, Eddington.

October, 2003: ESA drops Eddington.

- talks with Jørgen about Kepler collaboration pick up a little.

April, 2004: NASA drops all monetary support for Asteroseismology within the Science Team.

Tim and I had a mission, but no support. Jørgen and Hans had (Danish) support, but now no mission. Thus the origin of KASC.

How Kepler got its Sharp PSFs.

Kepler was supposed to have intentionally poor optics in order to deliver very soft PSFs. You probably don't know the story . . .

Kepler optics design plans and requirements, pre-2003:

"Pointing noise is suppressed . . . by **SPREADING** the **PSF OVER MANY PIXELS**." (emphasis original)
"The desired focus position produces PSFs with **<20% flux in the central pixel**." Uniform over field.

Mid-2003 — BALL Aerospace — the ball had been dropped in terms of implementing a soft PSF. As being built some PSFs have up to 68% light in central pixel, vast majority >30% flux, and severe field dependence.

A few M$ would fix, but 2003 not a time for asking for more money.
Emergency analyses initiated within science team to grapple with this!

Sharpest channel is at 63%, average 47%, lowest 28%. PSF is under sampled.
Good news: the channels with sharpest PSF deliver the best photometry.

American and European sides were competitive, sometimes dismissive of the other.

I maintained in ‘90s and early ‘00s that Kepler would outperform STARS/ Eddington for asteroseismology. I still believe that would have been true.

July 2009 — Benoît Mosser and Thierry Appourchaux, A&A submitted, “On detecting the large separation in the autocorrelation of stellar oscillation time series.”

“The Kepler mission compared to CoRoT will provide lower photometric performance . . . In 90 days, only the brightest F-type or the class IV targets will have . . . the large separation. In a 4-year run, only the brightest G dwarfs will deliver a clean seismic signature. . . The asteroseismic goal of Kepler is principally to derive information on stars hosting a planet, by the determination of the large separation.”

2005-mid-2009 —the revolution is nearly at hand

Exoplanets — discovery pace continues to accelerate, space with HST, MOST and COROT gains prominence, atmospheric probing becomes quasi-routine, transits + RVs important.

Asteroseismology — RV detections improve, impressive result on μ Ara by Bazot et al., Bouchy et al. 2005.

Has become a vibrant science, but without space only order 1 detection per year at **great** effort and resources.

COROT results by Michel et al 2008 on dwarfs are wonderful, but number stays small, **quality** still far from solar.

The promise of space photometry for both exoplanets and asteroseismology continues to grow. Anticipation fills the air.

2009 — The Space Photometry Revolution Begins.

De Ridder et al 2009, and Hekker et al 2009 publish **stunning results on Red Giant oscillations from COROT**, published in May, accepted in June respectively. Fears of prominent theorists (Jørgen for one) that red giants would not show non-radial modes of interest were dispelled!

To my mind **the positive results on red giants from COROT was the opening salvo in the space photometry revolution for our sciences.**

Kepler Mission data access was very restrictive in the early days.
During May and June 2009 I was at NASA Ames and the only person in the world with ready access to all the Short Cadence data.

Power spectra showed F and G star pulsations very clearly.
A plot of effective noise from Kp ~7-16 showed results near optimistic limits.
And it appeared that Nature was going to be generally co-operative.

The revolution was clearly at hand, and the community would know it whenever we managed to get the data distributed a little more.

The Revolution in Numbers

Tabulating the number of exoplanet and asteroseismic discoveries in 5 year intervals.

	<1994	1999	2004	2009	2014
Exoplanets	4	25	120	265	1,382
Asteroseismology	0	0	10	380	15,000

COROT results factor into 2005-2009, while Kepler starts in 2010-2014.

COROT fractions in any bin are small, except 2005-2009 asteroseismology where it dominated. Kepler dominates 2010-2014.

For exoplanets the Kepler + COROT fraction for 2010-2014 is about 50%, numerically it's not clear there was a revolution.

With consideration of qualitative advances there clearly has been a revolution in both fields due to space photometry.

How has the Space Photometry Revolution Changed our Sciences?

1994: quest was for discovery, any modestly believable result would do!

Now: a stunningly large number of rock-solid detections in both fields, AND a series of qualitative advances, e.g., discerning the demographics of planets across the rocky/gaseous boundary, probing the internal rotation and deep structural characteristics of red giants, and often results combining exoplanets and asteroseismology to strong interpretive effect.

A particle physics flavor:

1996

A PLANETARY COMPANION TO 70 VIRGINIS[1]

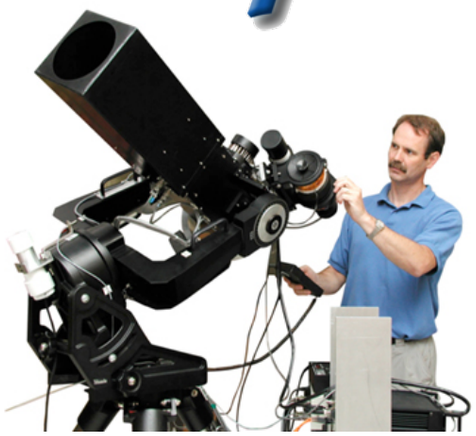
GEOFFREY W. MARCY[2] AND R. PAUL BUTLER[2]

2014

MASSES, RADII, AND ORBITS OF SMALL *KEPLER* PLANETS: THE TRANSITION FROM GASEOUS TO ROCKY PLANETS*

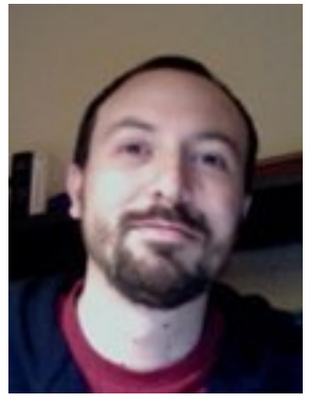
GEOFFREY W. MARCY[1], HOWARD ISAACSON[1], ANDREW W. HOWARD[2], JASON F. ROWE[3], JON M. JENKINS[4], STEPHEN T. BRYSON[3], DAVID W. LATHAM[5], STEVE B. HOWELL[3], THOMAS N. GAUTIER III[6], NATALIE M. BATALHA[3], LESLIE ROGERS[7], DAVID CIARDI[8], DEBRA A. FISCHER[9], RONALD L. GILLILAND[10], HANS KJELDSEN[11], JØRGEN CHRISTENSEN-DALSGAARD[11,12], DANIEL HUBER[3], WILLIAM J. CHAPLIN[11,13], SARBANI BASU[9], LARS A. BUCHHAVE[5,14], SAMUEL N. QUINN[5], WILLIAM J. BORUCKI[3], DAVID G. KOCH[3], ROGER HUNTER[3], DOUGLAS A. CALDWELL[4], JEFFREY VAN CLEVE[4], REA KOLBL[1], LAUREN M. WEISS[1], ERIK PETIGURA[1], SARA SEAGER[15], TIMOTHY MORTON[7], JOHN ASHER JOHNSON[7], SARAH BALLARD[16], CHRIS BURKE[4], WILLIAM D. COCHRAN[17], MICHAEL ENDL[17], PHILLIP MACQUEEN[17], MARK E. EVERETT[18], JACK J. LISSAUER[3], ERIC B. FORD[19], GUILLERMO TORRES[5], FRANCOIS FRESSIN[5], TIMOTHY M. BROWN[20], JASON H. STEFFEN[21], DAVID CHARBONNEAU[5], GIBOR S. BASRI[1], DIMITAR D. SASSELOV[5], JOSHUA WINN[15], ROBERTO SANCHIS-OJEDA[15], JESSIE CHRISTIANSEN[3], ELISABETH ADAMS[22], CHRISTOPHER HENZE[3], ANDREA DUPREE[5], DANIEL C. FABRYCKY[23], JONATHAN J. FORTNEY[24], JILL TARTER[4], MATTHEW J. HOLMAN[5], PETER TENENBAUM[4], AVI SHPORER[7], PHILIP W. LUCAS[25], WILLIAM F. WELSH[26], JEROME A. OROSZ[26], T. R. BEDDING[27], T. L. CAMPANTE[11,13], G. R. DAVIES[11,13], Y. ELSWORTH[11,13], R. HANDBERG[11,13], S. HEKKER[28,29], C. KAROFF[11], S. D. KAWALER[30], M. N. LUND[11], M. LUNDKVIST[11], T. S. METCALFE[31], A. MIGLIO[11,13], V. SILVA AGUIRRE[11], D. STELLO[27], T. R. WHITE[27], ALAN BOSS[32], EDNA DEVORE[4], ALAN GOULD[33], ANDREJ PRSA[34], ERIC AGOL[16], THOMAS BARCLAY[35], JEFF COUGHLIN[35], ERIK BRUGAMYER[36], FERGAL MULLALLY[4], ELISA V. QUINTANA[4], MARTIN STILL[35], SUSAN E. THOMPSON[4], DAVID MORRISON[3], JOSEPH D. TWICKEN[4], JEAN-MICHEL DÉSERT[5], JOSH CARTER[15], JUSTIN R. CREPP[37], GUILLAUME HÉBRARD[38,39], ALEXANDRE SANTERNE[40,41], CLAIRE MOUTOU[42], CHARLIE SOBECK[3], DOUGLAS HUDGINS[43], MICHAEL R. HAAS[3], PAUL ROBERTSON[17,19], JORGE LILLO-BOX[44], AND DAVID BARRADO[44]

Kepler Closing Thoughts.



In 1994 ARAA “Asteroseismology” Tim Brown and I could only discuss foundations, and hopes for the future.

In 2013 ARAA “Asteroseismology of Solar-Type and Red-Giant Stars” Bill Chaplin and Andrea Miglio: “We are entering a golden era for stellar physics . . . it was the launch of the French-led COROT and the NASA Kepler Mission that heralded major breakthroughs for the field”



It has been an exciting time to participate in; our sciences have indeed undergone revolutions due to space photometry.

Success breeds continuation — the future with TESS, PLATO and other missions will provide compelling advances in the decades to come.