Exploring the Long-term and Extreme Variability of Stars

Sumin Tang

Advisor: Jonathan Grindlay

Thesis Talk, May 2, 2012

Acknowledgement

- Advisor: Josh Grindlay
- DASCH team:

  Edward Los, Alison Doane, Bob Simcoe, Jaime Pepper, David Sliski, Silas Laycock, Mathieu Servillat;

  Many volunteers: George Champine, Chase Green, Julia Hardy, Ray Kenison, Jim Ostiguy, Steve Siok, Alan Sliski, Bill Toomey, volunteers at AMNH

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- Committee members:

  Dimitar Sasselov, Avi Loeb, Rosanne Di Stefano,

  Howard Bond; Martin Elvis

- Many colleagues:

  Bob Kurucz, Max Moe, Jonathan McDowell, Dave Latham, Jose Fernandez, Sam Quinn, Lars Buchhave, Allyson Bieryla, Scott Kenyon, Andrea Dupree, Anna Frebel, Francesca Civano, Soren Meibom,Warren Brown, Ruth Murray-Clay, Matthew Holman, Branden Allen, Maureen van den Berg, Paul Green, Emilio Falco, Perry Berlind, Nelson Caldwell, Mike Calkins, Jessica Mink, Bill Wyatt, Susan Tokarz; Jerry Orosz, Ronald Gilliland

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- All fellow grad students:

  Gongjie Li, Ann Mao, Heng Hao, Roman Shcherbakov, Sasha Tchekhovskoi, Li Zeng, Wen-fai Fong, Joey Nelson, Meng Su and many others
- Faculty members:

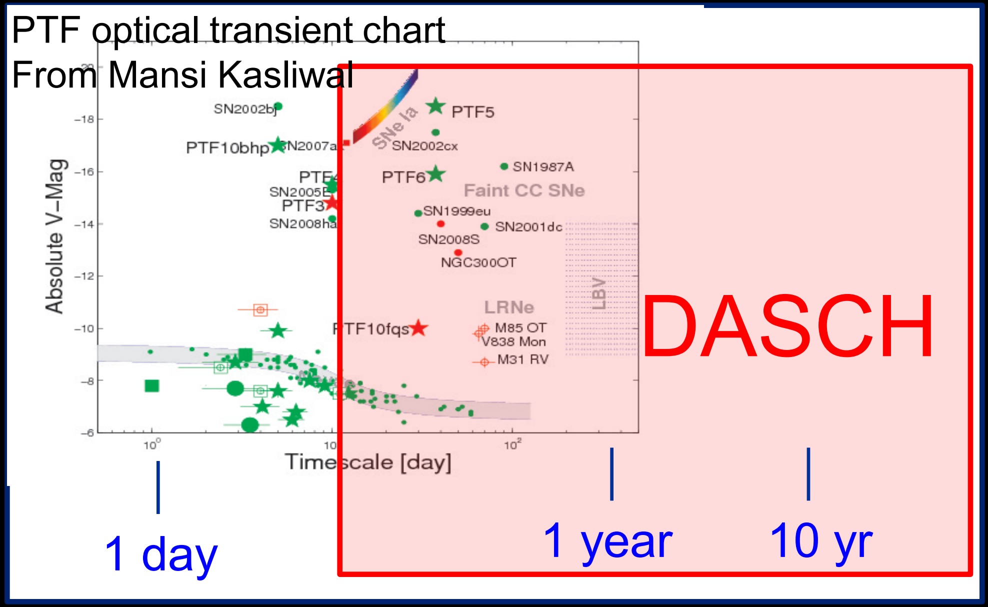
  Julia Lee, Jim Moran, Ramesh Narayan, Irwin Shapiro, Edo Berger, David Charbonneau, Bob Kirshner.
- Admin: Peg Herlihy, Donna Adams, Jean Collins, Donna Wyatt, Uma Mirani, Carol Knell; CF/HEA help
- CfA climbing community and many other friends

First question: what are variable stars?

- A star is called variable if its brightness changes over time
- The variability could be extrinsic, such as eclipse and lensing; or intrinsic, such as pulsation, flares, accretion variability, or explosions
- The definition depends on the variability amplitude and timescale: all stars are variable if the measurement accuracy is high enough (see e.g. Kepler), or if we could wait long enough
- My thesis is on ‘long-term’ (timescales from days to 100 years) and ‘extreme’ (amplitude>~0.5 mag) variables with DASCH (Digital Access of a Sky Century@Harvard)

Second question: Why study long-term variables with DASCH?

- They are there, mostly un-explored



- They provide important information about the physical processes involved, most of which are not clearly understood yet: dust processes, magnetic cycles of stars, accretion, nuclear burning on WDs… Variability is the way stars 'talk' to us. We want to decipher 'the message' to learn how they work.

- And we do not want to wait another 80+ years to study variations over 100 years (while we do have the data here in the cabinets)

Outline

- What I do: Introduction to DASCH
- How I do it: Photometry and Defect Filtering
  (*Tang et al. 2012c; Laycock, Tang, et al. 2010*)
- What I get - Scientific Results:
  - The Kepler Field
    - Planet Host Stars (*Tang et al. 2012b*)
    - Variable Search and Catalog (*Tang et al. 2012d*)
  - Individual Long-term Variables
    - Peculiar K Giant Variables (*Tang et al. 2010; 2012e*)
    - KU Cyg: a 5-yr Dust Accretion Event (*Tang et al. 2011*)
    - A 10-yr Nova-like Outburst (*Tang et al. 2012a*)
  - Two Other Post-Thesis Discoveries
- Summary

Harvard Plate Stacks

Half a million photographic plates from 1885-1992

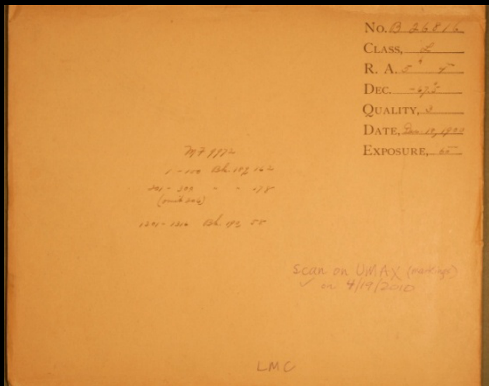
Including 83 plate series (each typically represents a single telescope) from 22 observatories (MA, CA, South Africa, New Zealand, Peru…)

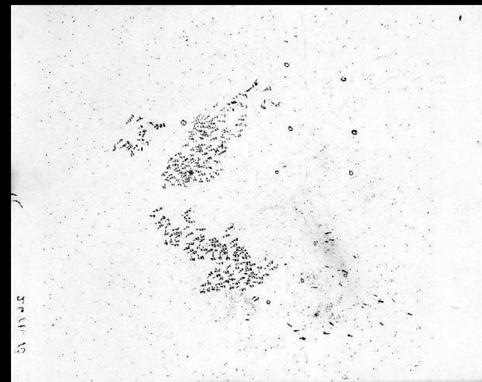
Bring the plates back to Harvard was not an easy job….

> One shipping story that stands out is that of the freighter SS *Robin Goodfellow*. On July 25, 1944, while carrying a shipment of plates from South Africa, it was torpedoed and sunk by the German submarine *U-862* in the South Atlantic. Ironically, the *U-862* was transporting valuable cargo to the Japanese, including a shipment of optical glass. But despite these losses, the surviving collection at Harvard is still a quarter of the world's entire inventory of approximately 2 million plates.

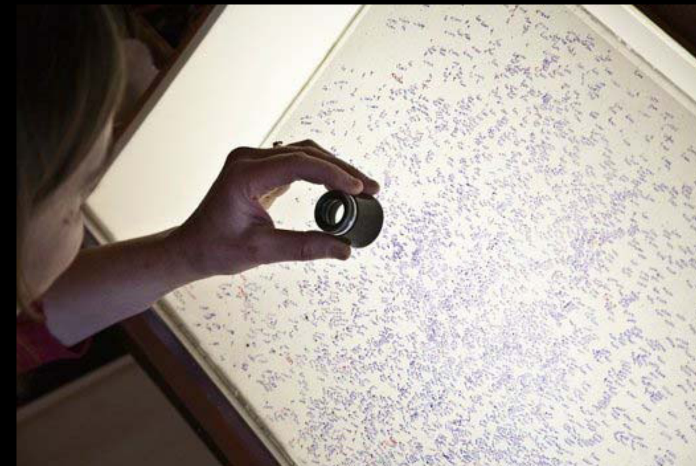
-- Stephen Lieber, *Sky & Telescope*, Mar 2010

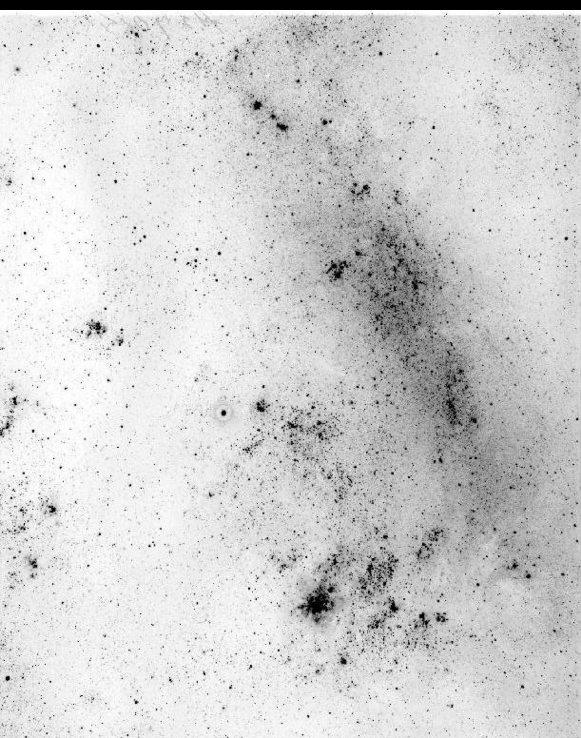
Plate b26816, LMC. Dec 18, 1900, Arequipa, Peru.
Used by Henrietta Leavitt on Cepheid stars.





Traditional way





DASCH scanner

Simcoe et al. 2006

DASCH (Digital Access to a Sky Century@Harvard)

PI: Grindlay

Digitize and Measure the Harvard Plates to open the ~100yr TD Window

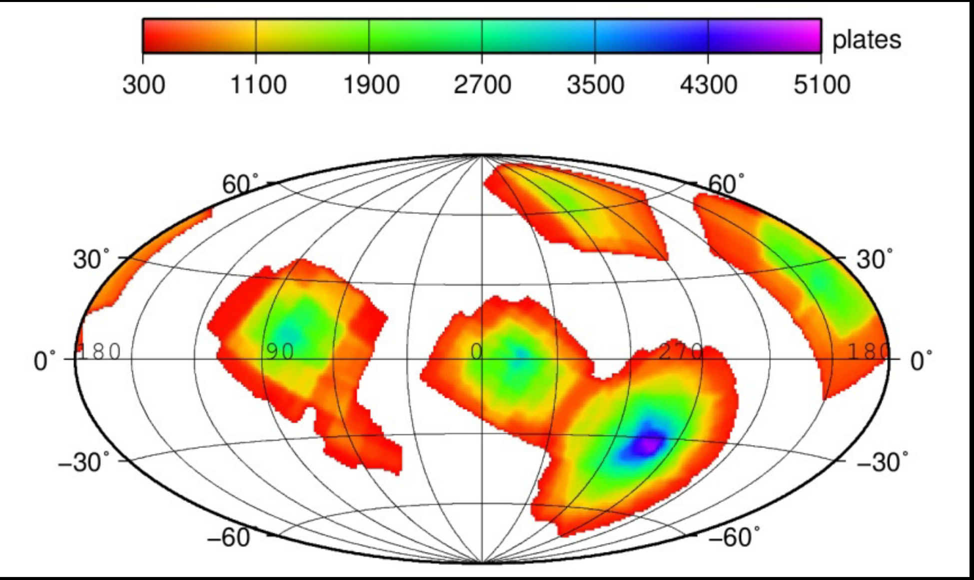
- ~500,000 photographic plates between 1880s-1980s covering the whole sky (*Grindlay et al. 2009*).
- ~500-1000 measurements for each object with B<14 (up to 18 mag in some regions)
- Astrometry: 0.8-3 arcsec

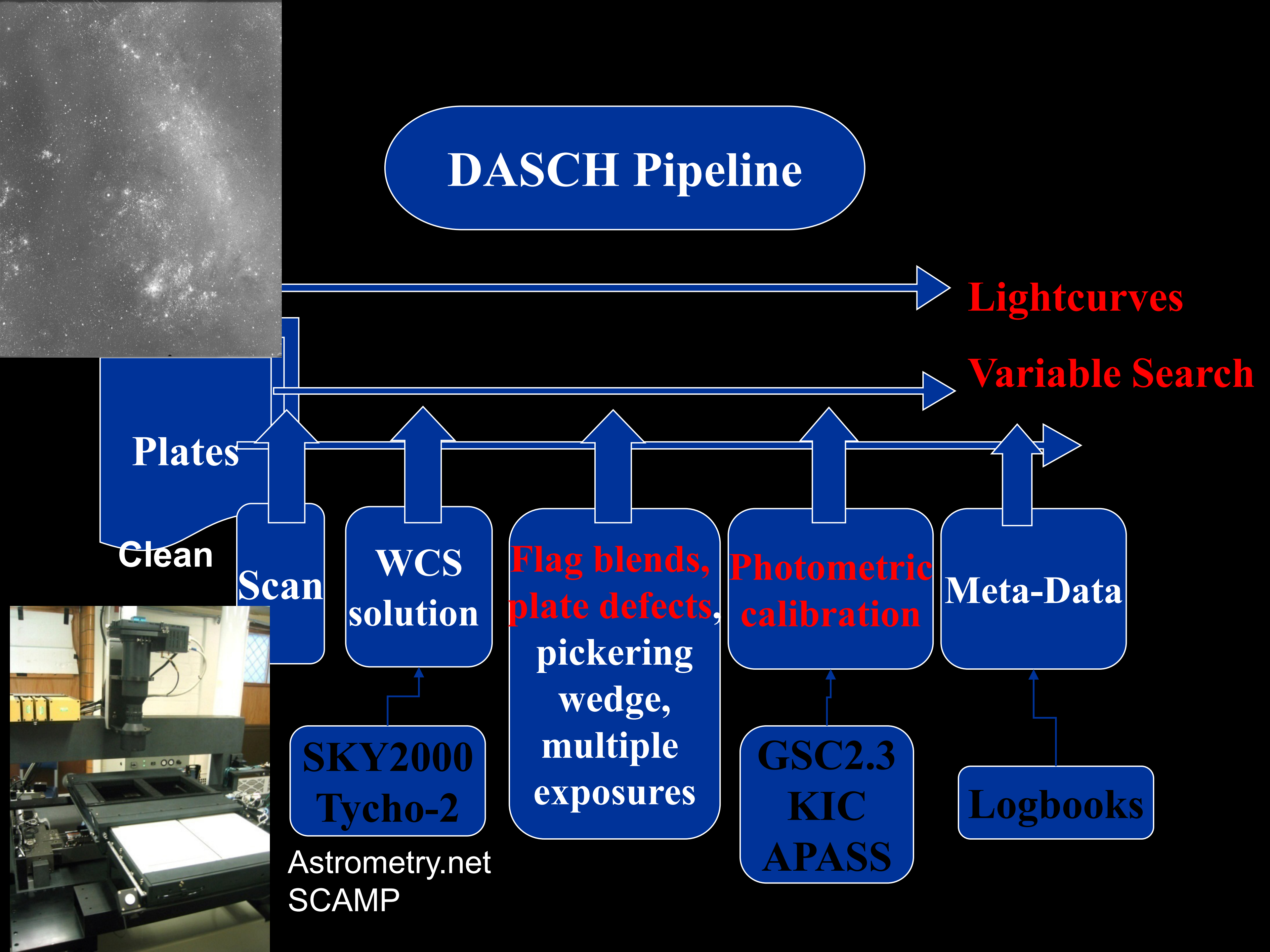
  Photometry: 0.1-0.13 mag (*Laycock et al. 2010; Tang et al. 2012c*).

- Two advantages of DASCH:
  - ✓ Long-term variables
  - ✓ Rare bright variables

~22,800 plates scanned (4.5%)
2.3×10^9 magnitude measurements

(If 1 measurement/sec => 73 years)




DASCH Pipeline
Lightcurves
Variable Search
Plates
Clean
Scan
WCS solution
Flag blends, plate defects, pickering wedge, multiple exposures
Photometric calibration
Meta-Data
SKY2000
Tycho-2
Astrometry.net
SCAMP
GSC2.3
KIC
APASS
Logbooks

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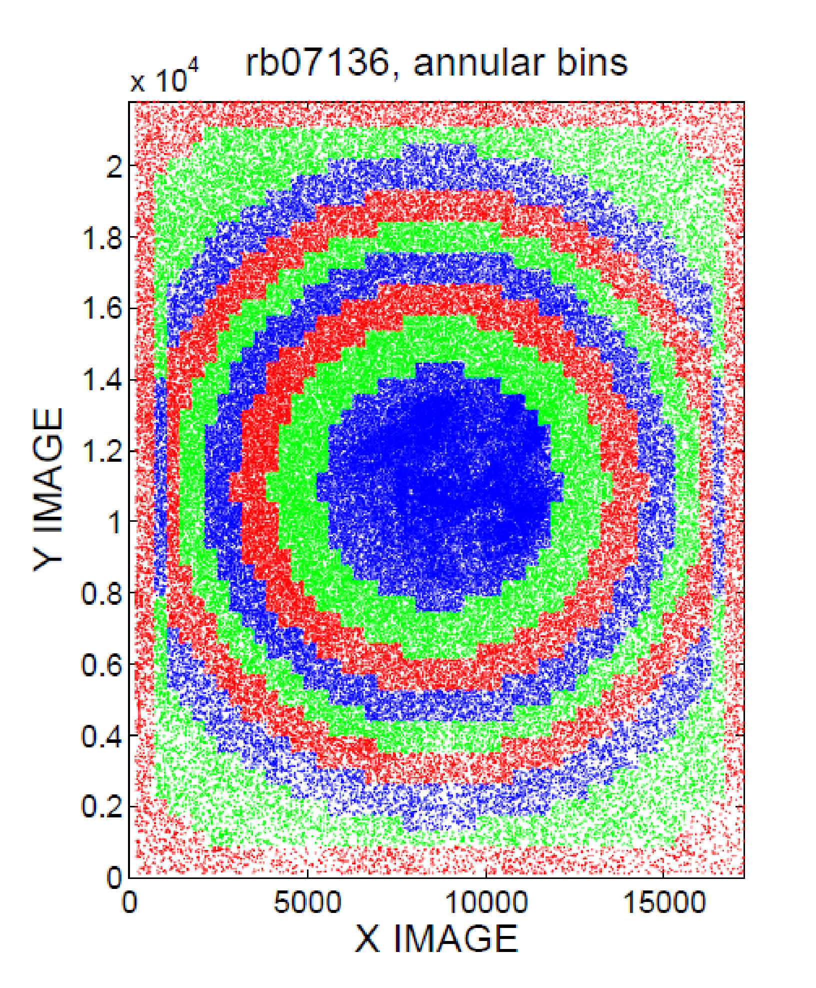
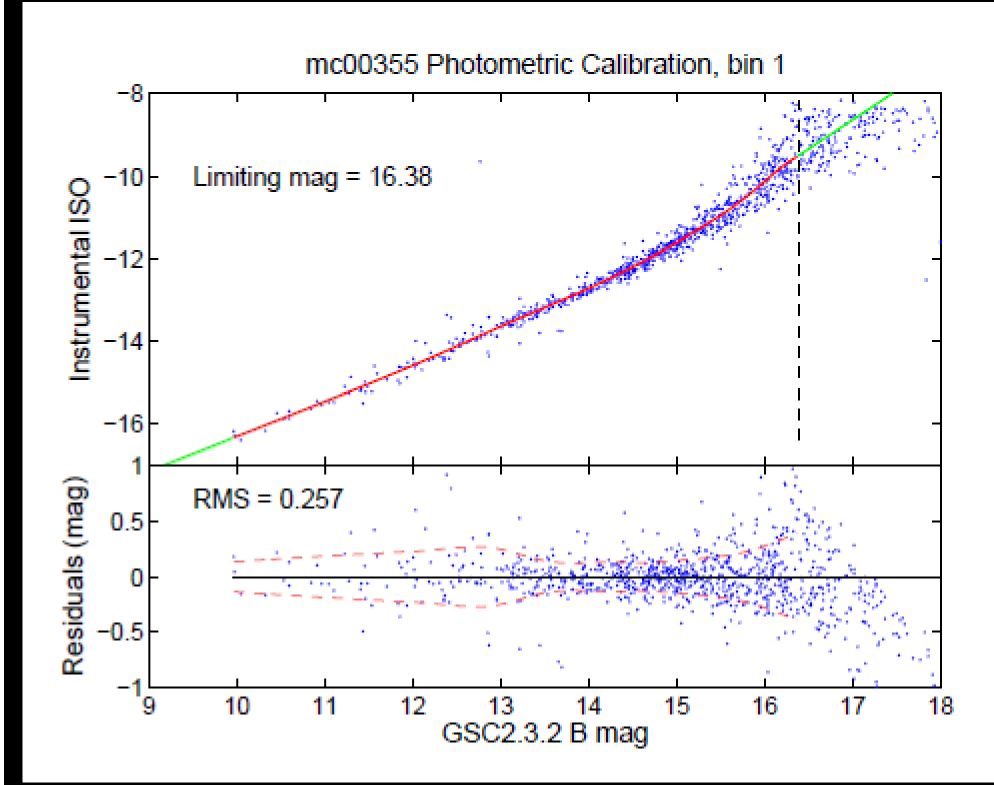
DASCH Photometry

Tang et al. 2012c;
Laycock, Tang, et al. 2010, AJ, 140, 1062

9 annular bins: to correct vignetting

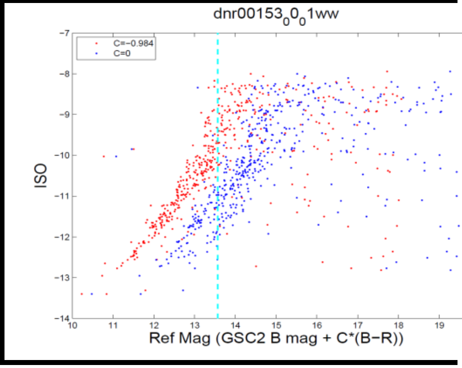
Thousands of stars in each annular bin

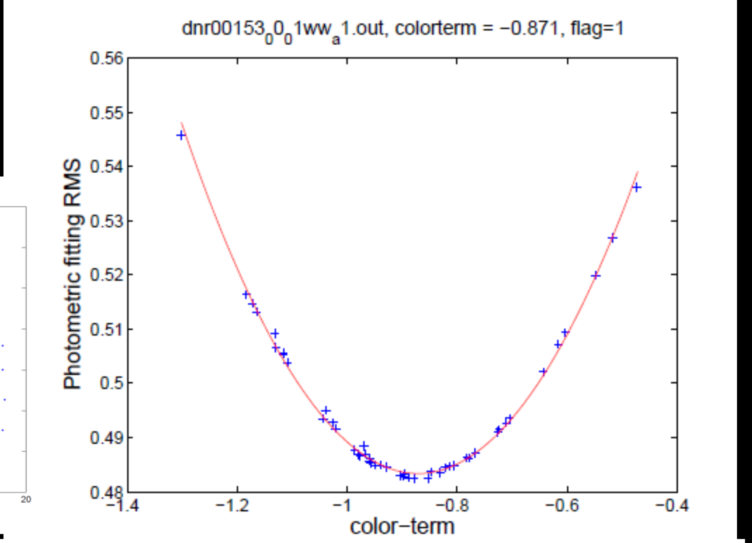


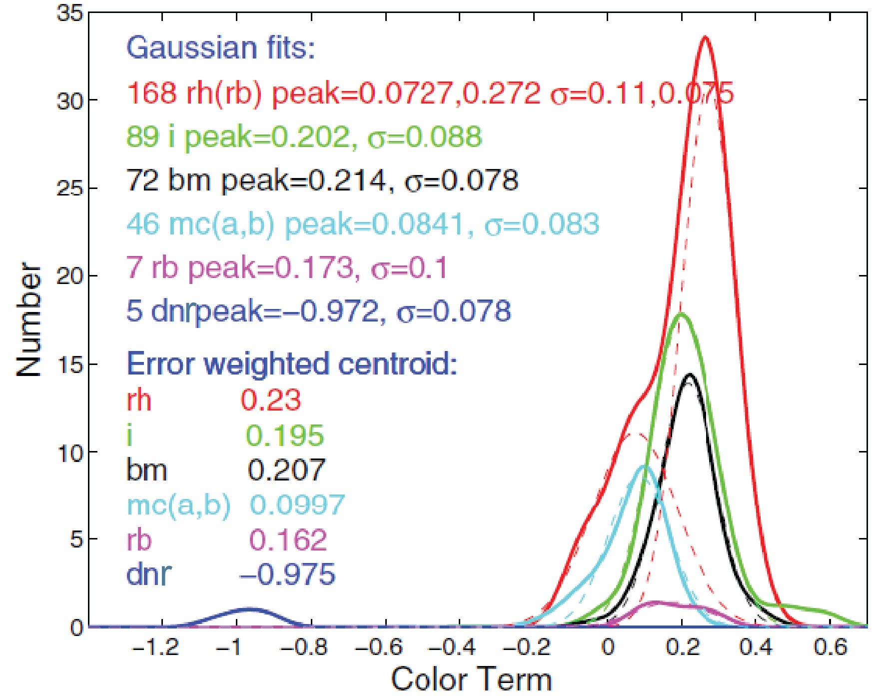


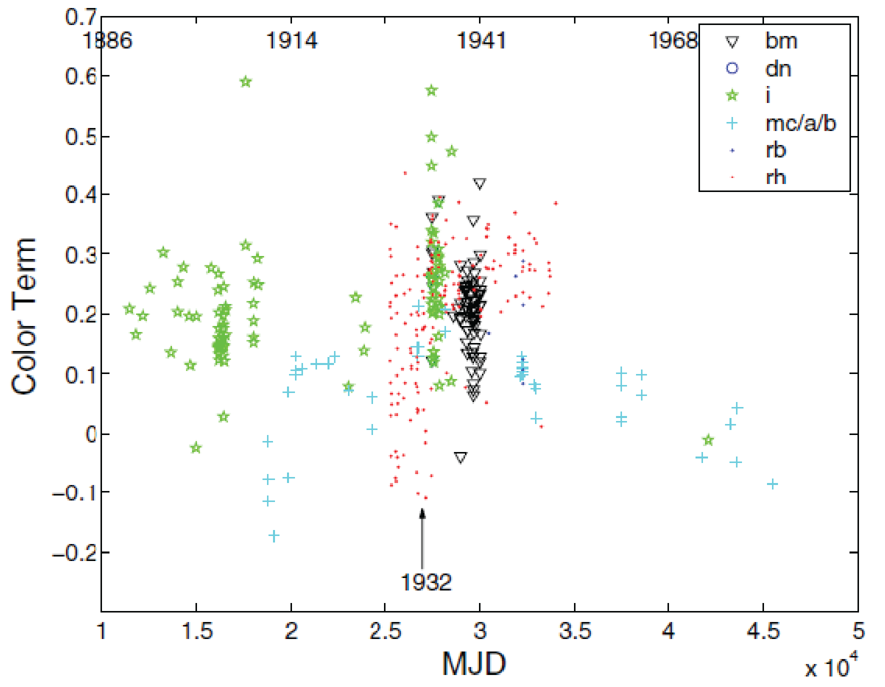
Color-term fitting

To derive the color-responses of the plates, by minimizing rms in the calibration curve









Local calibration using neighbors with similar magnitudes

To correct the inhomogeneity of plates,
we divide each plate into 400 local bins

Tang et al. 2012c

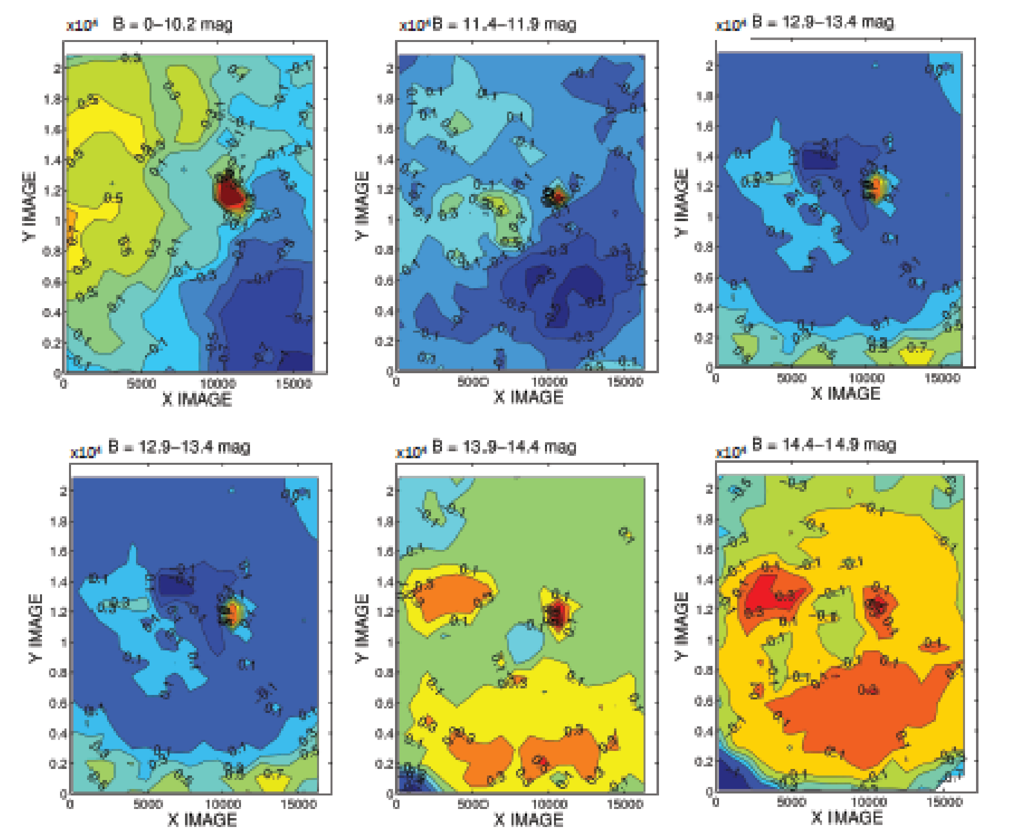
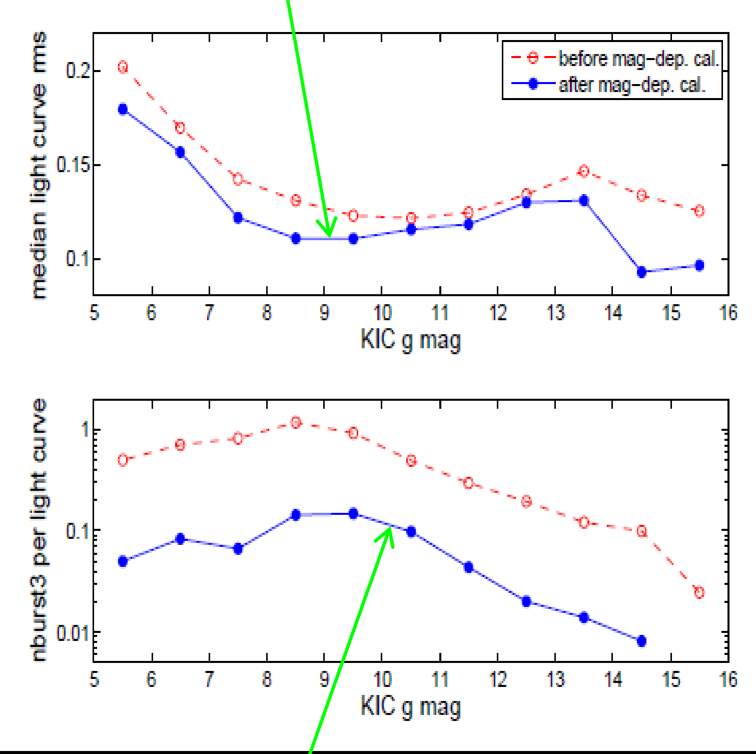


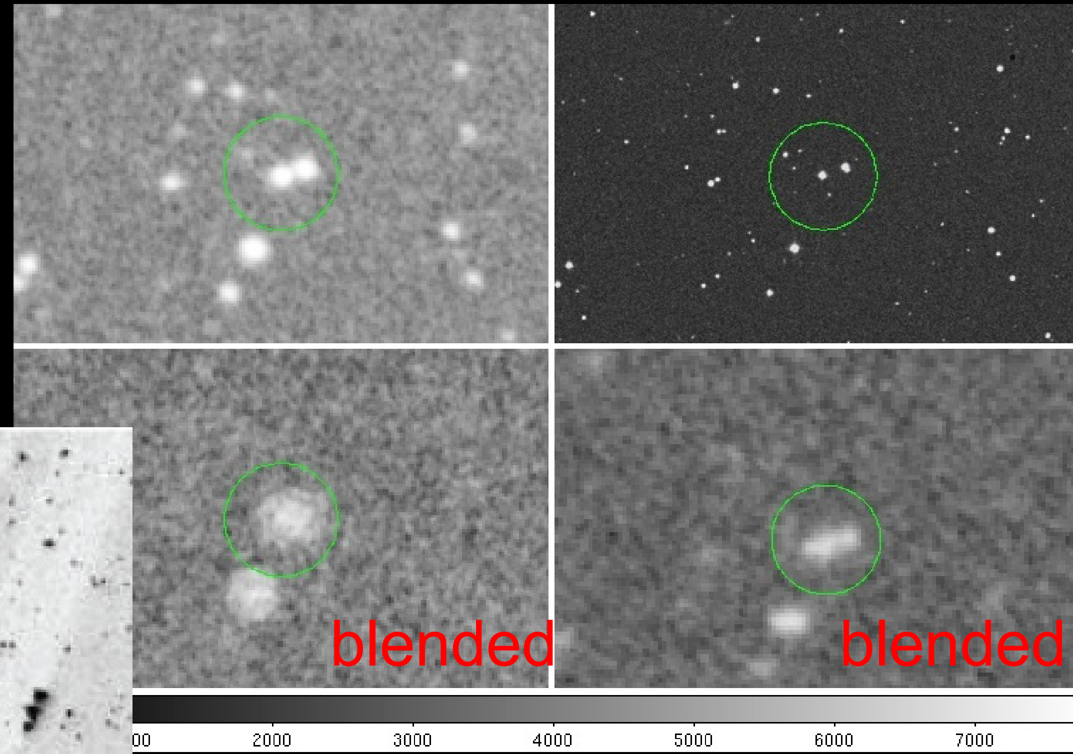
Figure 2.13.— Magnitude residual (plate magnitude - catalog magnitude) contour of plate rh07136 for stars in different magnitude bins. The X and Y axis are in units of pixels.

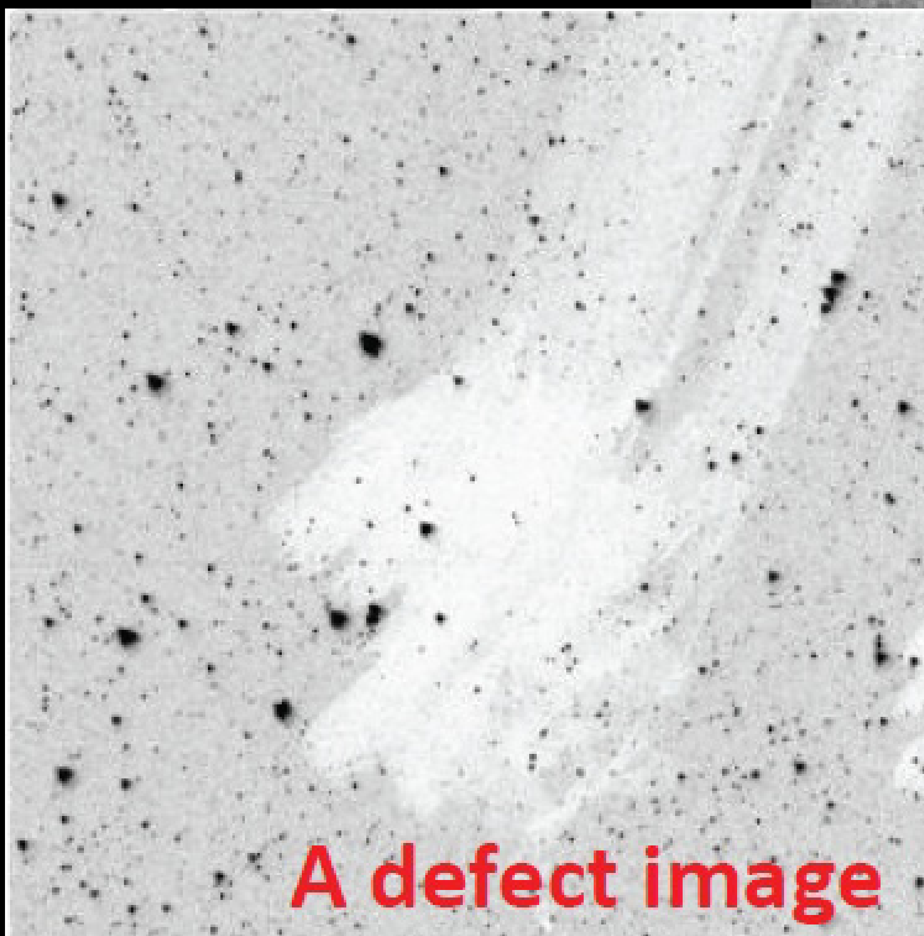
Photometry accuracy:
0.1-0.13 mag

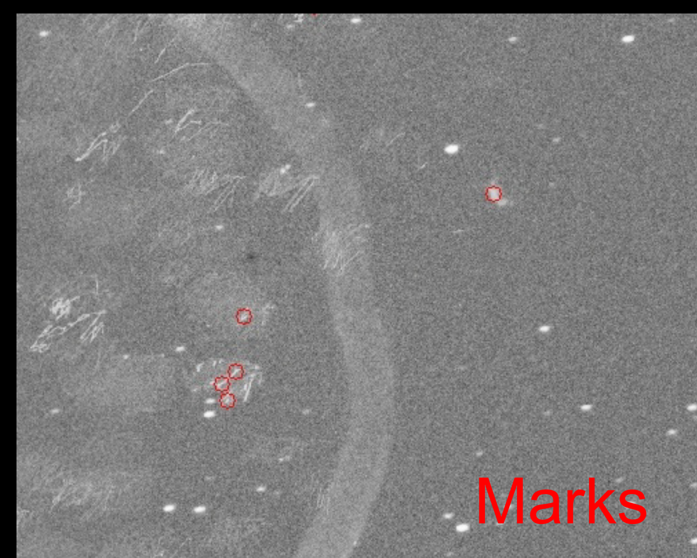


Number of outliers per lc:
reduced by one order of magnitude

Life is not easy…



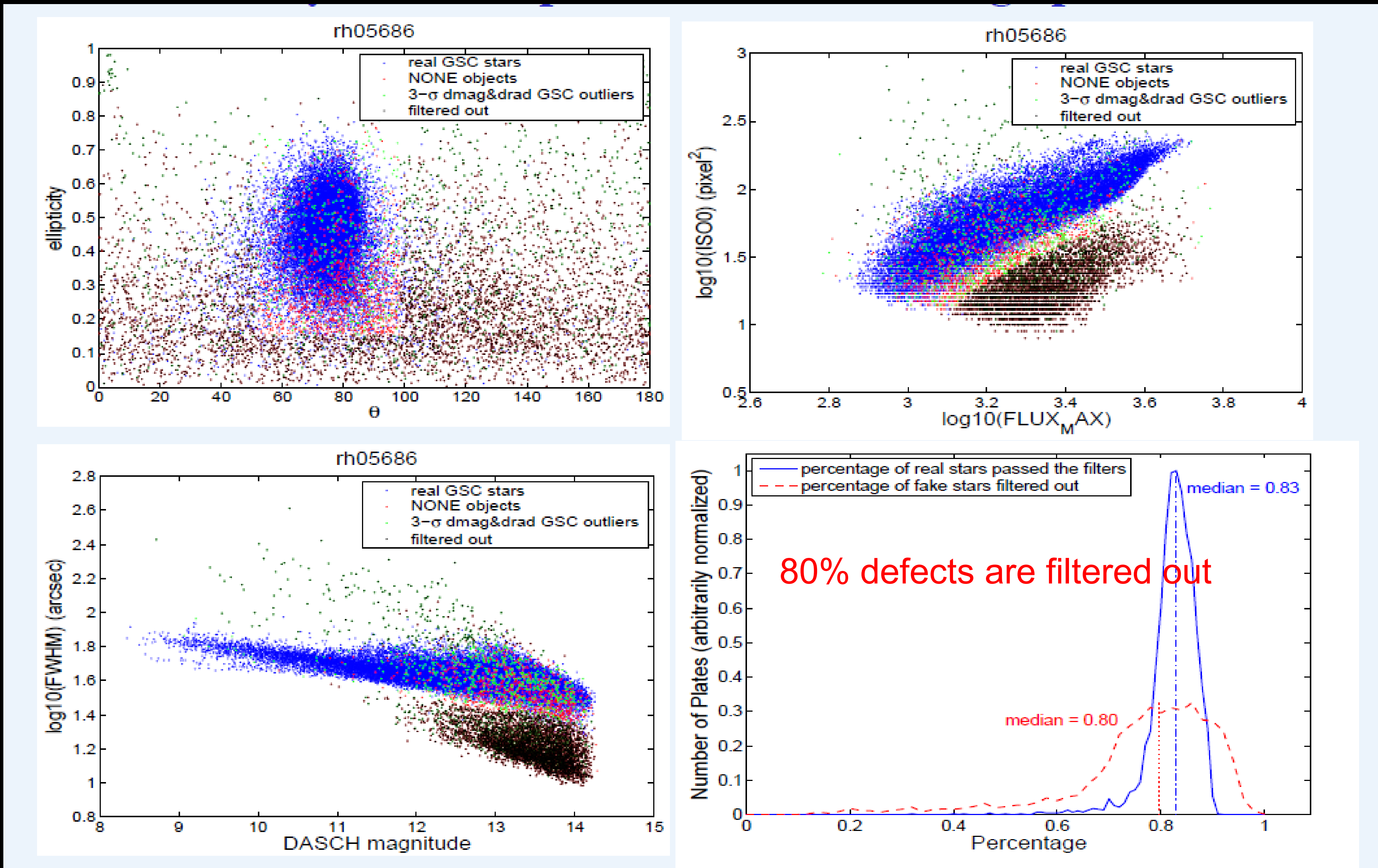




To find a real variable is like looking for a needle in a haystack….
Have to get rid of dubious signals

Use SExtractor parameters to filter out the defects

Tang et al. 2012c



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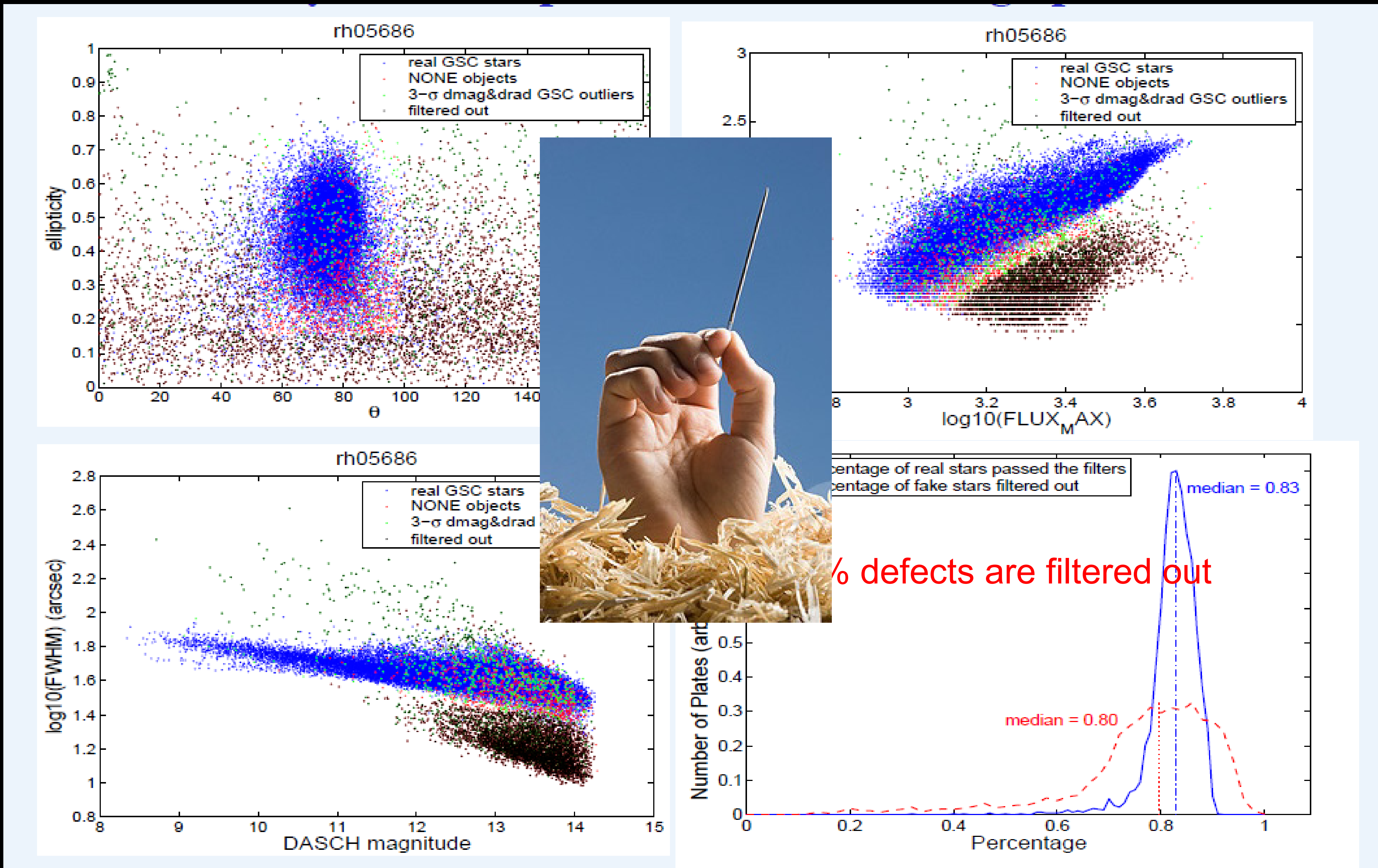

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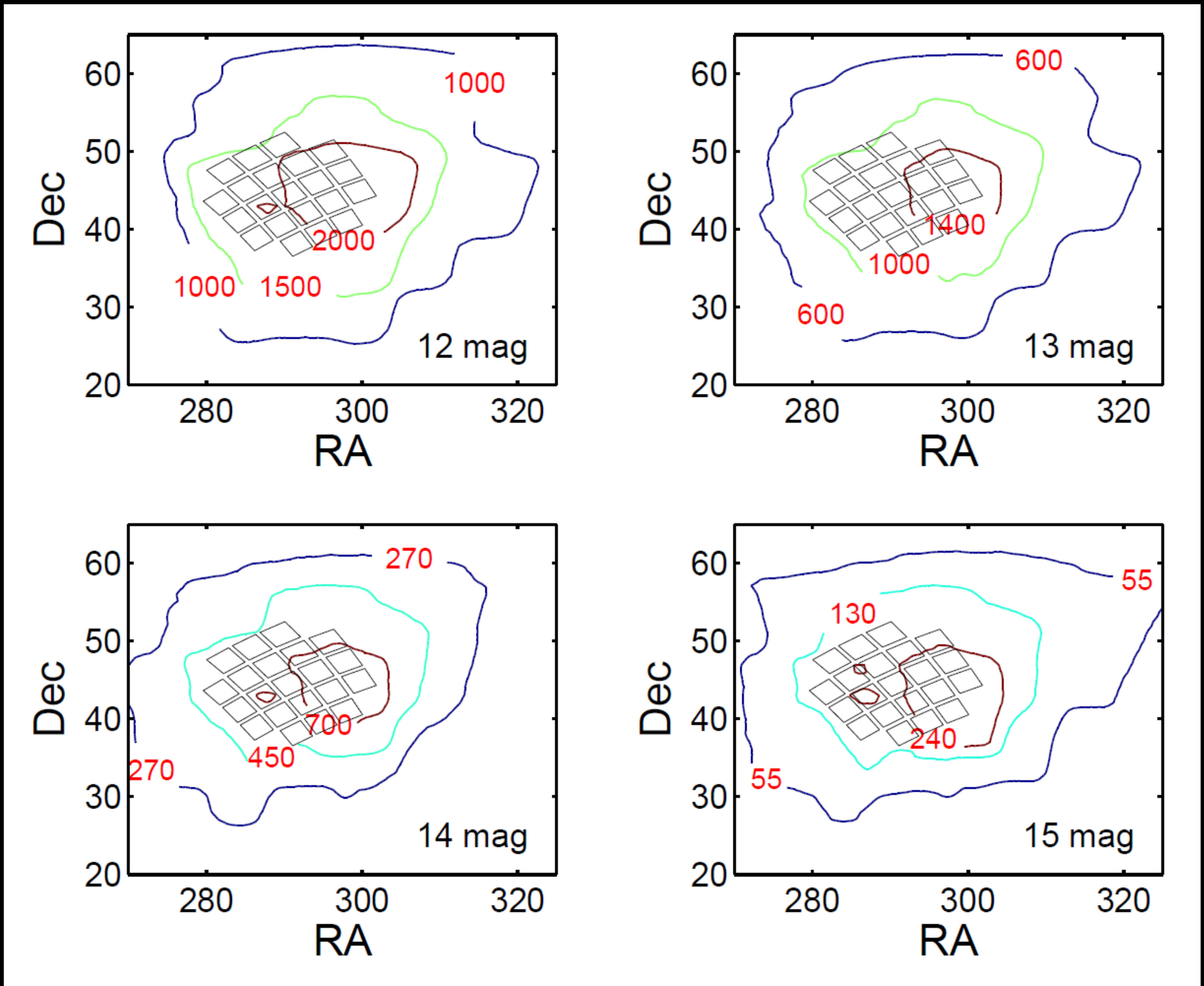
DASCH Coverage in the Kepler Field

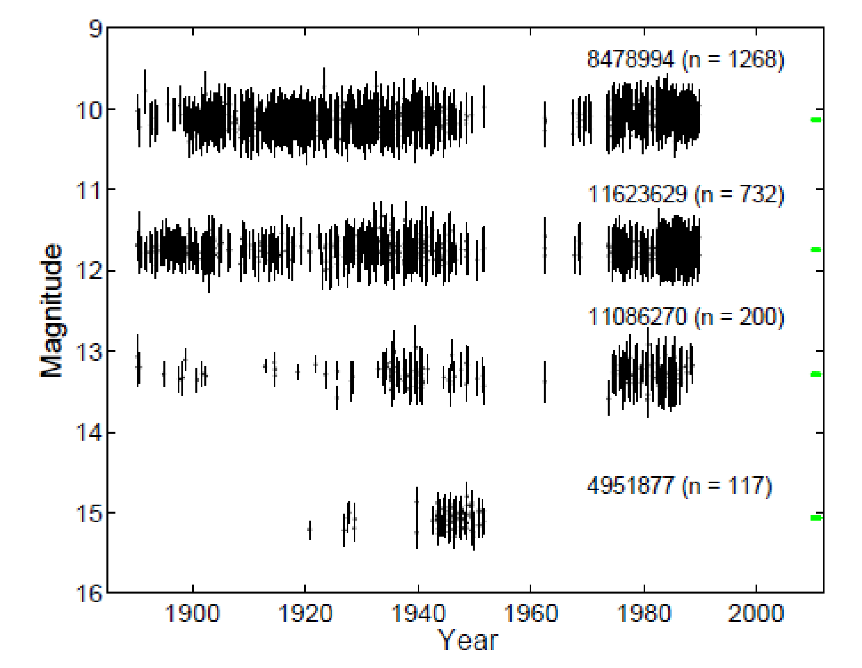
(relatively limited deep coverage compared to other fields)

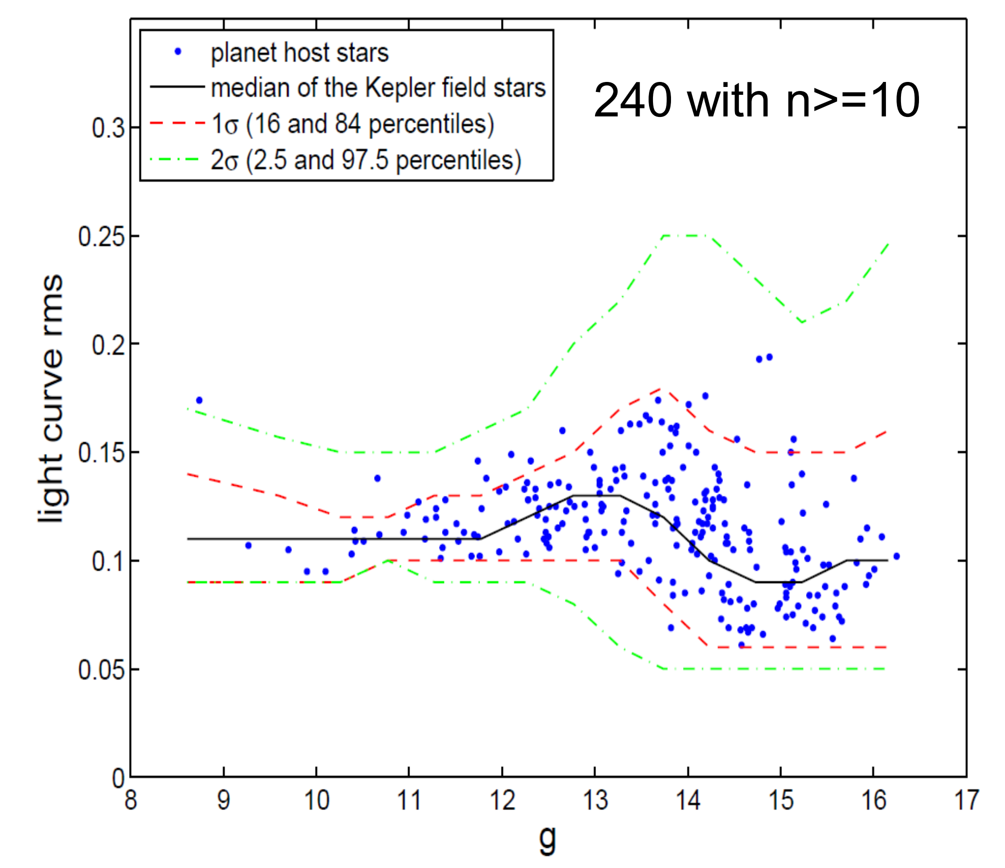


Kepler planet-candidate host stars

Tang et al. 2012b, AJ, submitted

Example light curves:

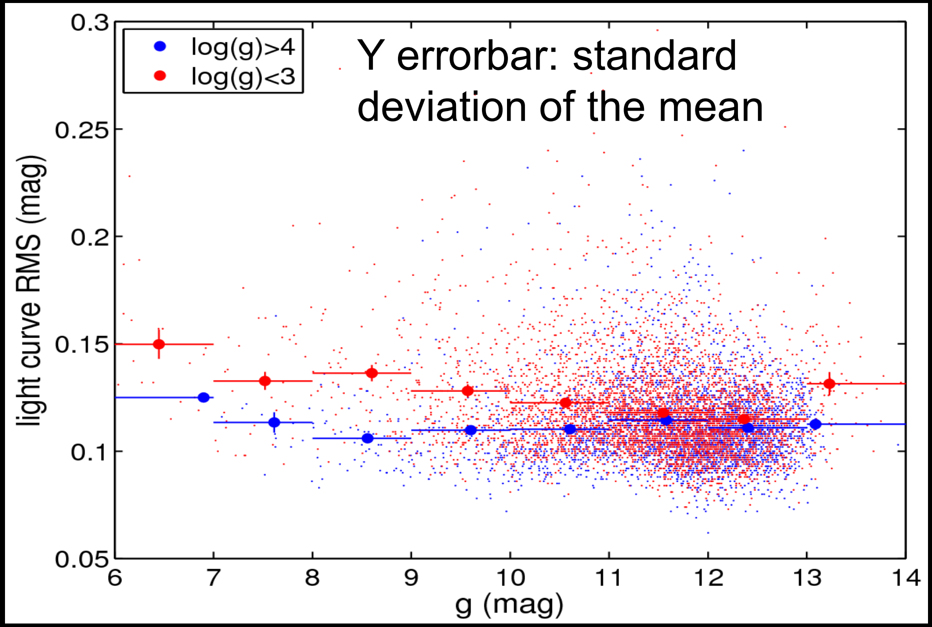




No variation detected for bright ones with good DASCH coverage

Good news for the habitability of the plants.

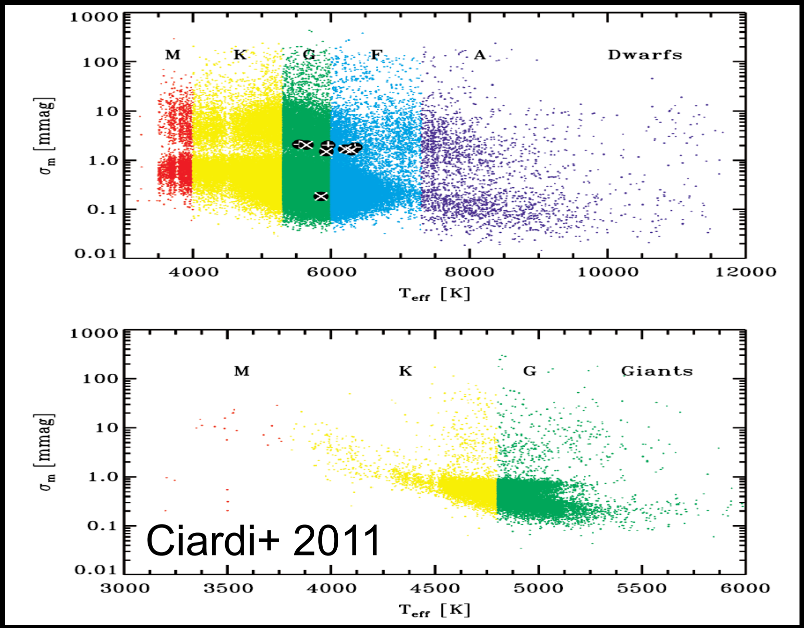
Main sequence vs giants
DASCH (100yr)



Kepler Q1 (33d)

Dwarfs: 0.01% to 1% variations

Giants: 0.01% to 0.1% variations



Variations on different timescales are probing different physical processes. Extrapolate does not work, and we cannot predict the 10-100 yr variation by looking at short timescale data, even if the data are extremely accurate. The value of DASCH is not only to discovery (new) variables, but what's more important, is to study the long-term behavior of stars and to explore the reasons which drive the variation.

Variable Search in the Kepler Fields

Tang et al. 2012d

Compare the light curve statistics locally in each sub-field

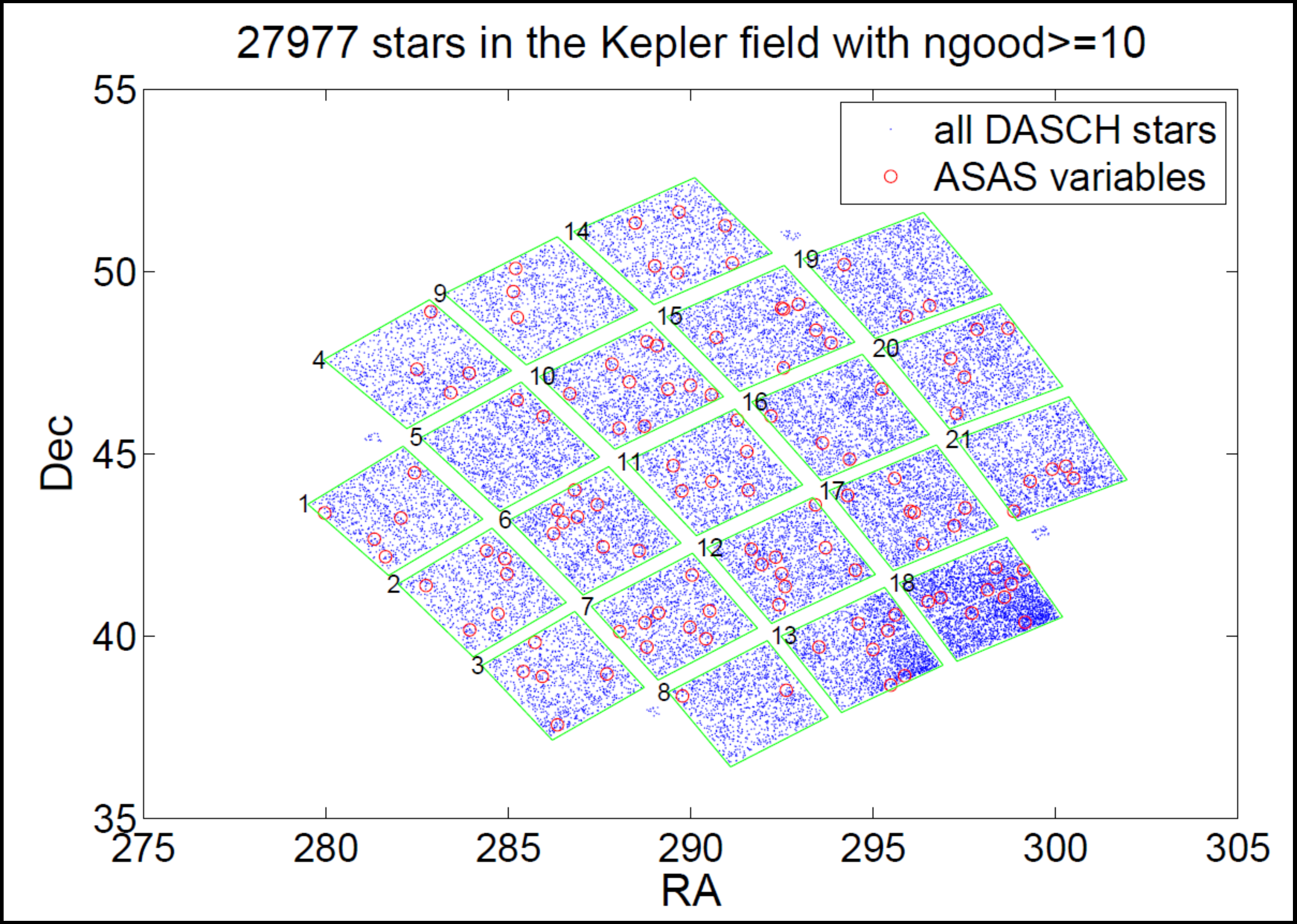
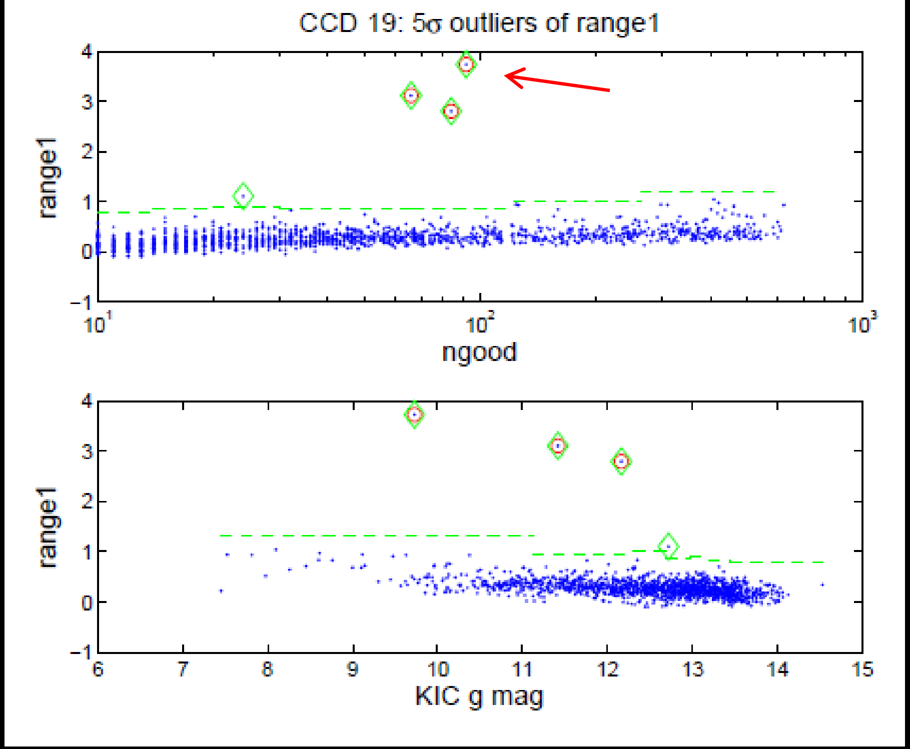
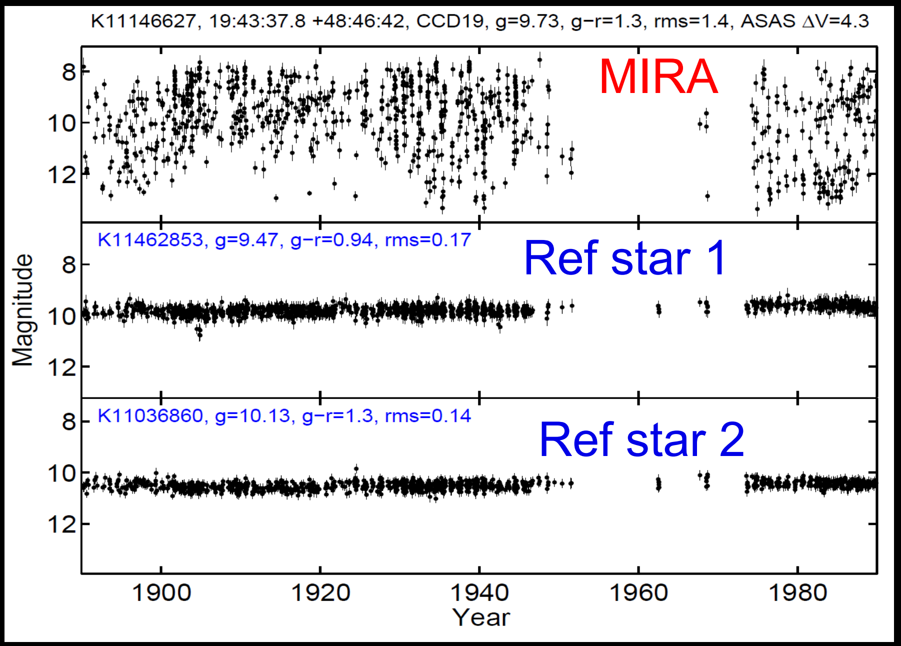


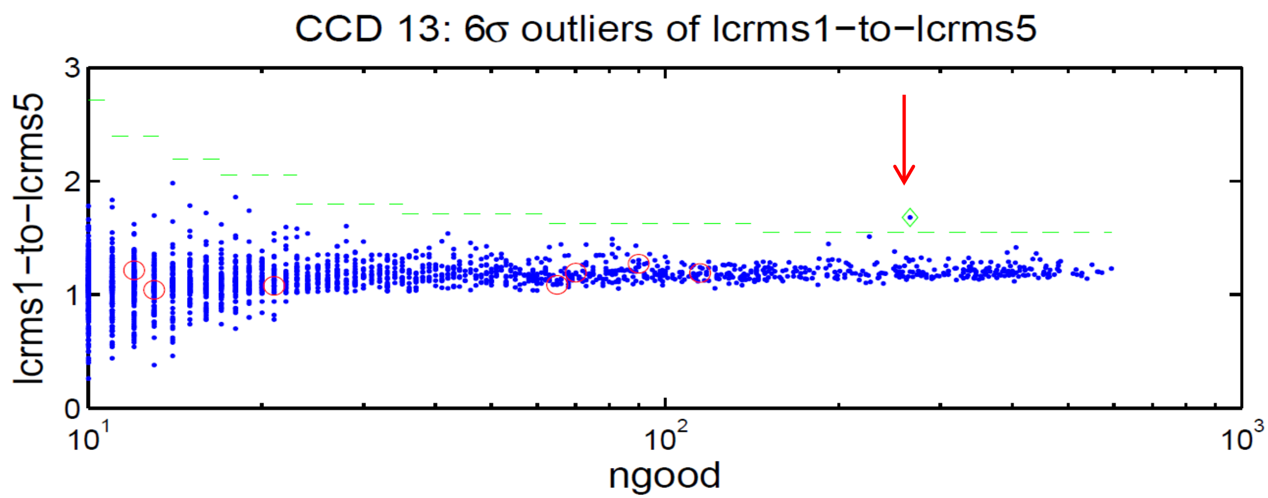
Table 2.1: Statistical measurements in the summary table

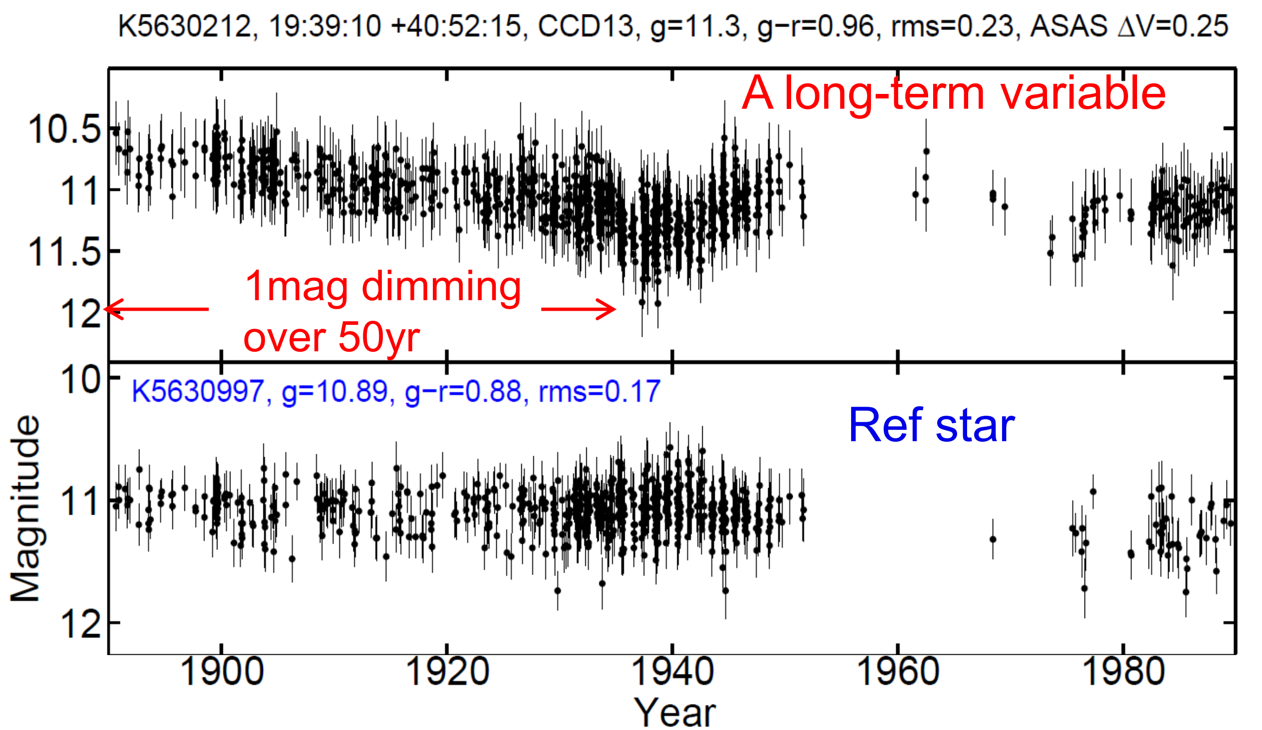
Parameter	Description
	Light curve amplitude and rms:
range_local	difference between the brightest and the faintest points, minus the sum of their errors
range_local2	similar to range_local, but after removing the brightest and the faintest points.
lightcurverms1	light curve rms after 4 iterations of 5σ clipping
	rms of light curve residuals after de-trending:
lightcurverms2	de-trended using smooth(x,y,0.4, 'lowess')
lightcurverms3	de-trended using smooth(y,0.8, 'lowess')
lightcurverms4	de-trended using smooth(y,10, 'sgolay')
lightcurverms5	de-trended using smooth(y,15, 'loess')
	Number of outburst and dip points:
nburst	number of points $\geq$ 0.8 mag brighter than the median value
nburst2	number of points $\geq$ 0.5 mag brighter than the median value
nburst3	number of points $\geq$ 0.4 mag brighter than the median value
nburst4	number of points $\geq 3\sigma$ brighter than the median value,
	where σ is the median value of photometry uncertainty in the light curve
ndip	number of points $\geq$ 0.8 mag fainter than the median value
ndip2	number of points $\geq$ 0.5 mag fainter than the median value
ndip3	number of points $\geq$ 0.4 mag fainter than the median value
ndip4	number of points $\geq 3\sigma$ fainter than the median value
ndev2	number of points $\geq 2\sigma$ brighter or fainter than the median value
ndev3	number of points $\geq 3\sigma$ brighter or fainter than the median value
	Adjacent points in 'burst' or 'dip':
adjacentburstdip	a measure of the number of adjacent nburst3/4 and ndip3/4 points
adjacentburstdip2	a measure of the number of >5 adjacent nburst3/4 and ndip3/4 points
adjacentburstdip3	a measure of the number of >7 adjacent nburst3/4 and ndip3/4 points
	Parameters used to remove dubious variables:
magvsracorr	correlation coefficient between light curve magnitude and ra
magvsdeccorr	correlation coefficient between light curve magnitude and dec
magvslimitingcorr	correlation coefficient between light curve magnitude and plate limiting mag
Malmquist_factor	clipped median DASCH magnitude of 20 deepest plates
	− clipped median DASCH magnitude of 20 shallowest plates using 'good' points
Malmquist_factorB	similar to Malmquist_factor but also includes defects, low altitude,
	uncertain date and second quality plates



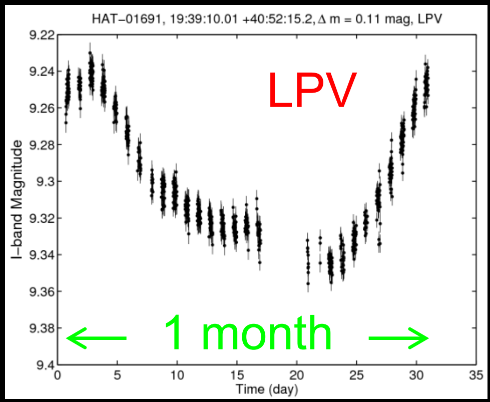


Example 2: a long-term variable

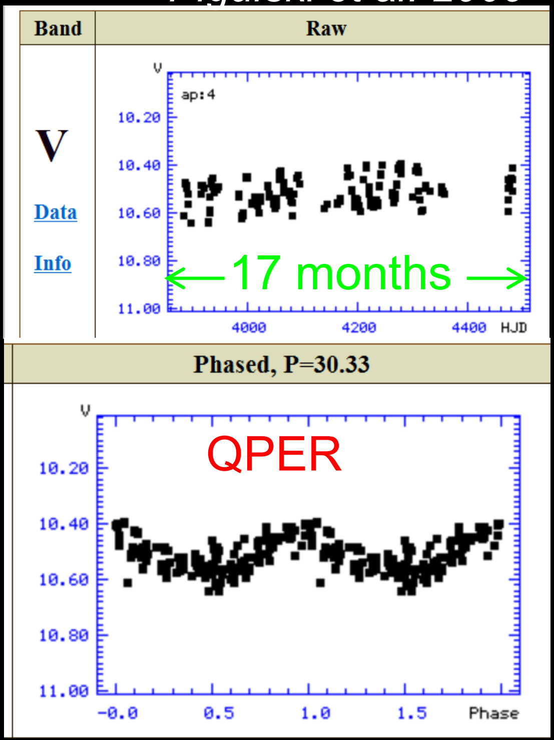




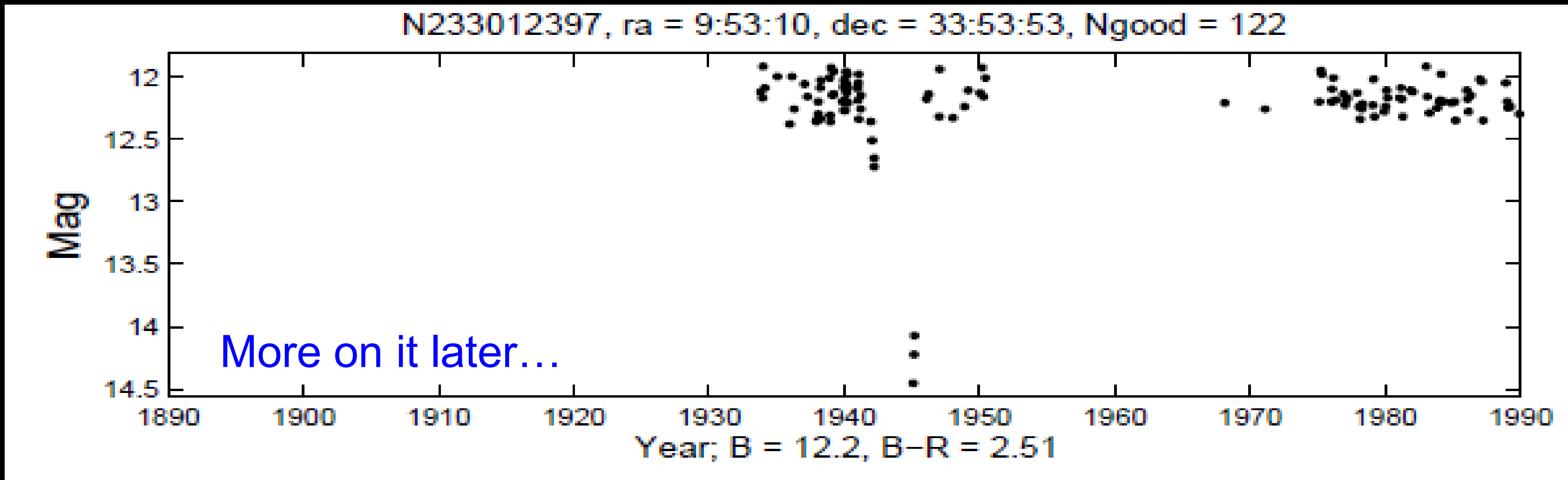
HATnet light curve
Hartman et al. 2004



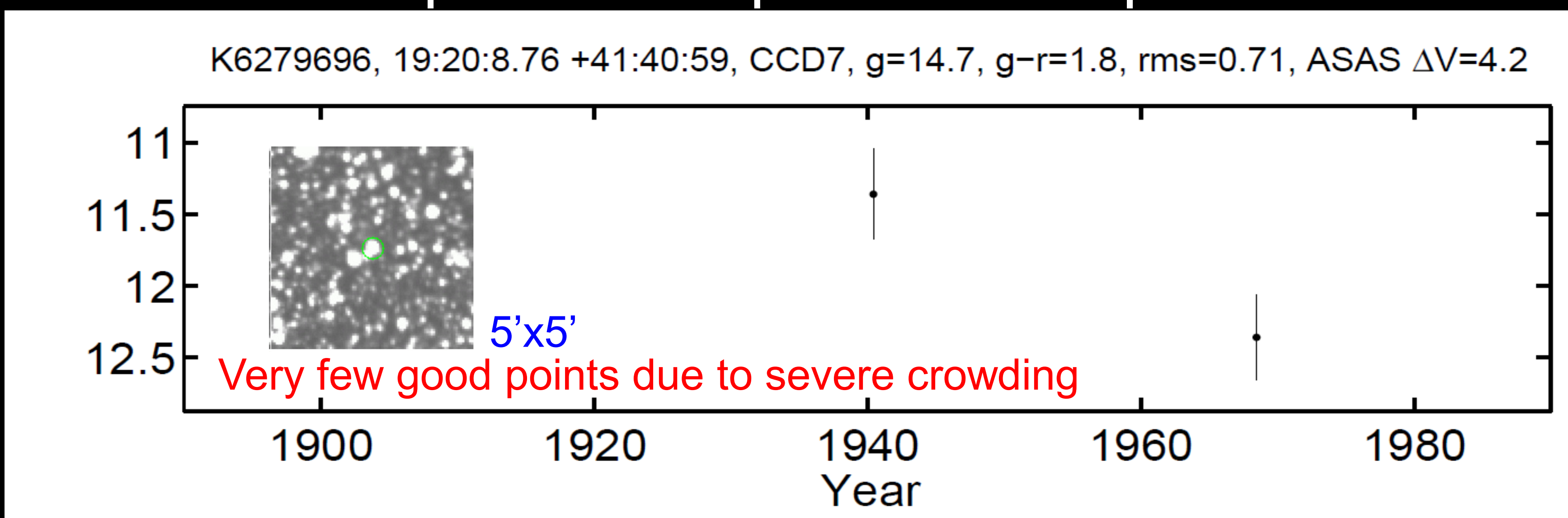
ASAS light curve
Pigulski et al. 2009



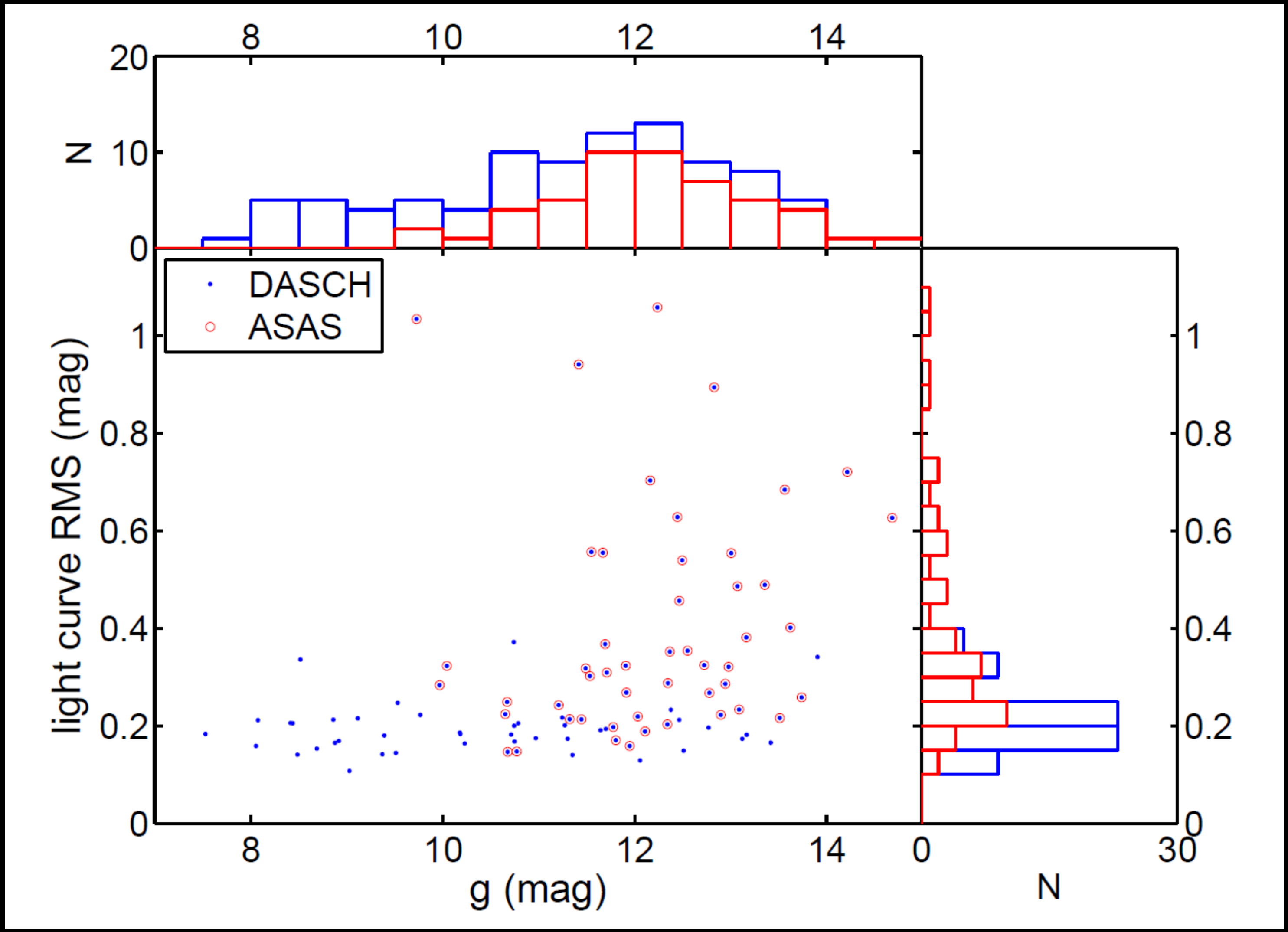
Example 3: adjacent dip points



Example 4: multiple outburst points

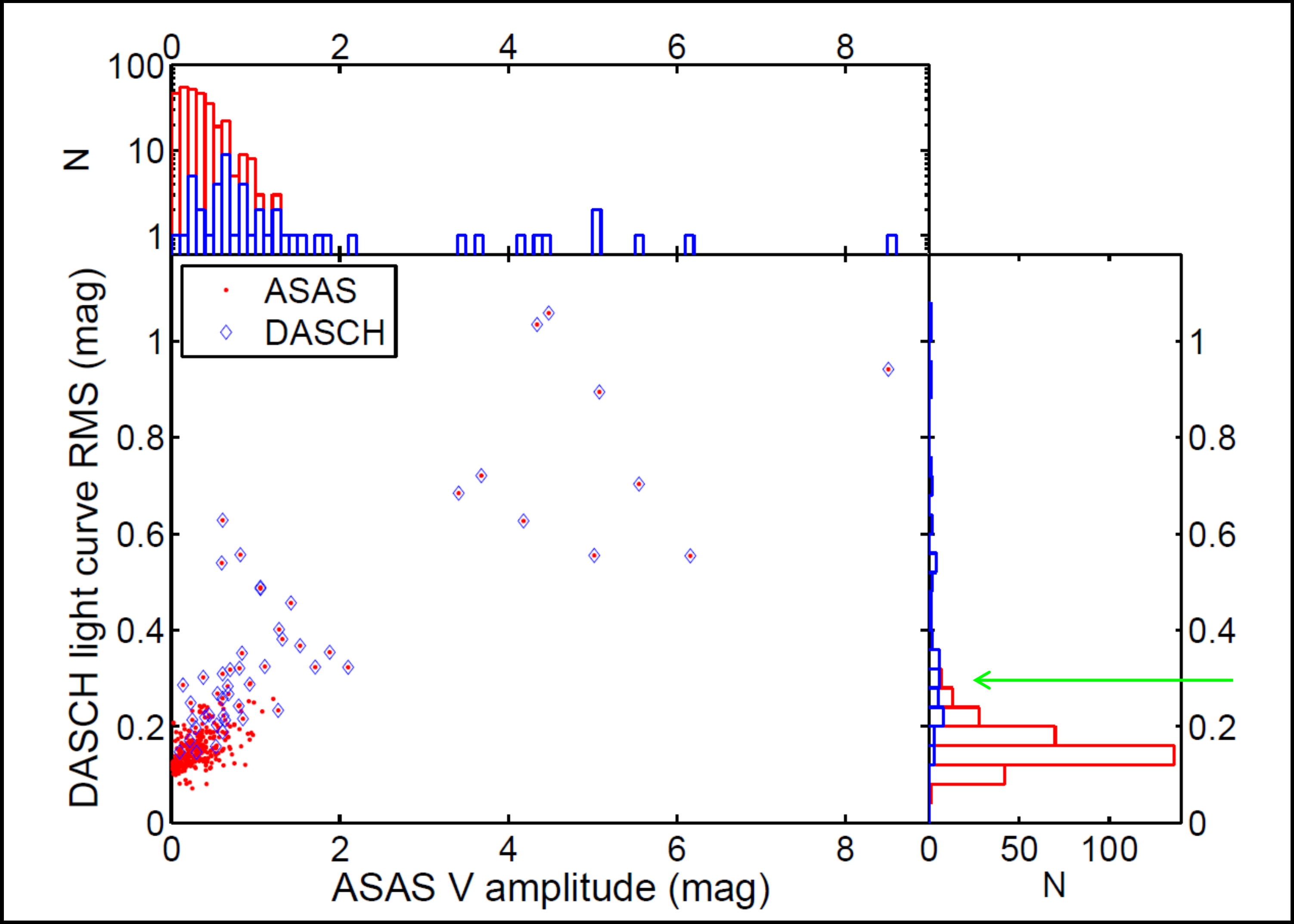


Results: 92 Variable Candidates in the Kepler FOV; 50 of them are ASAS variables



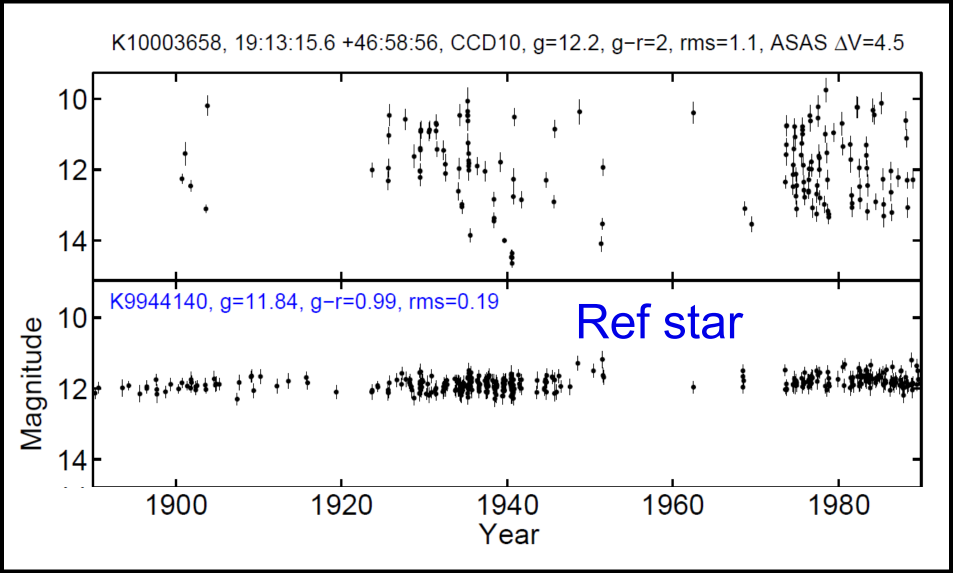
ASAS saturation limit: V~8.5 mag (*Pojmanski 2002*)

All (28/28) rms>0.3 mag,
and 92% (34/37) rms>0.25 mag
ASAS variables are found to be variables in DASCH

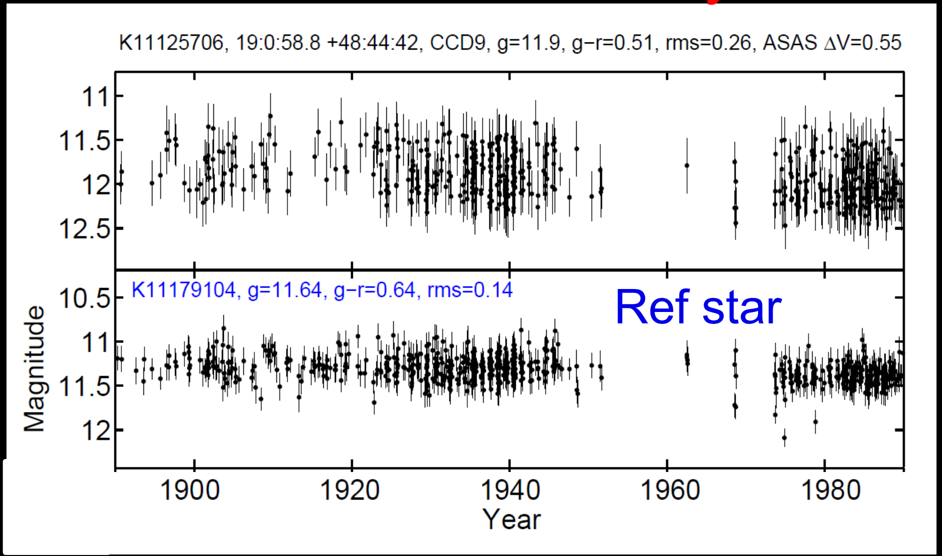


DASCH light curve examples

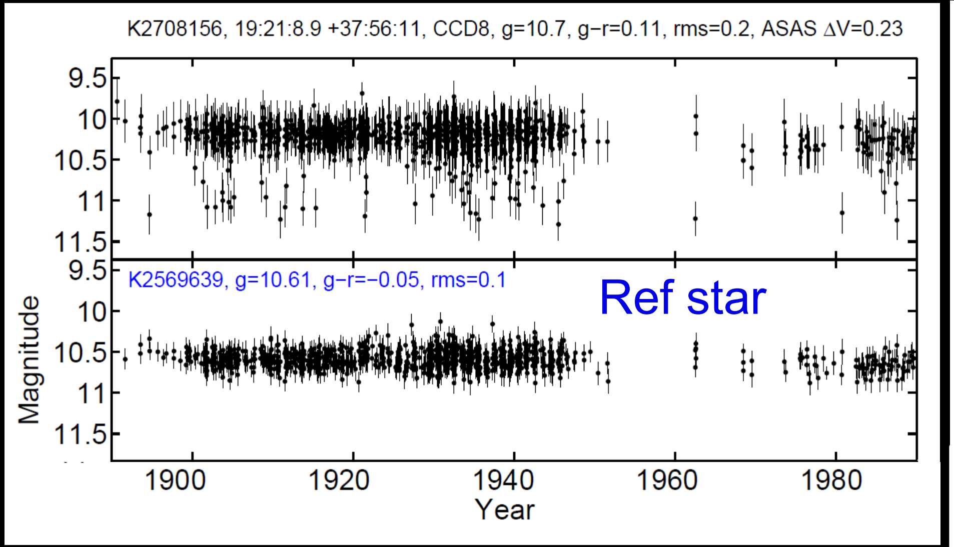
ASAS Mira



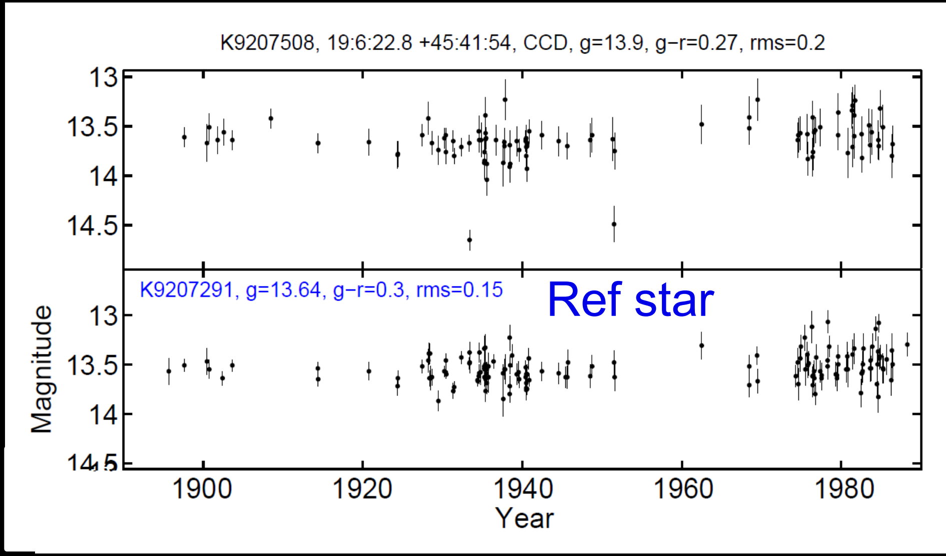
ASAS RR Lyr



ASAS EB

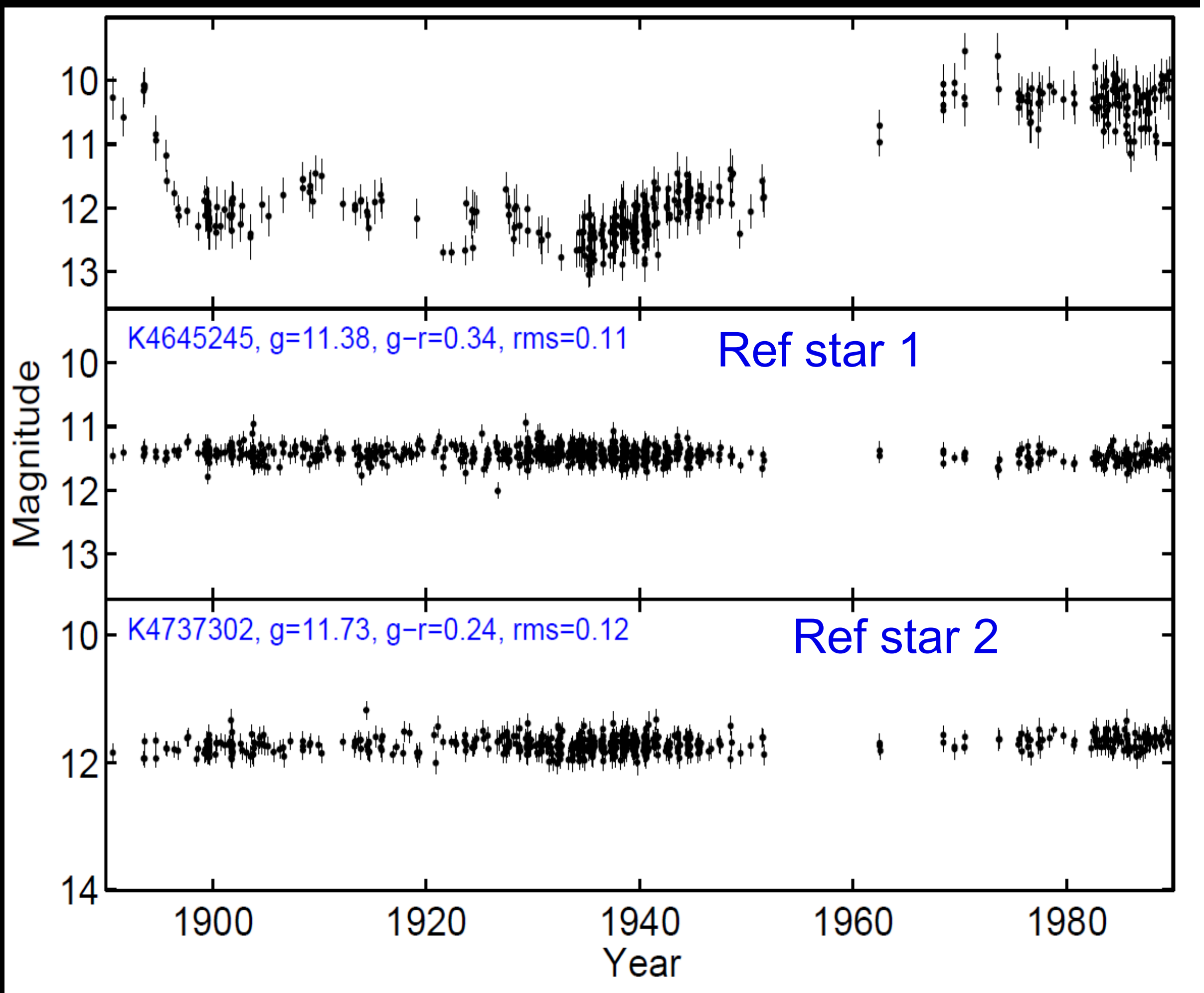


An EB not in ASAS cat.

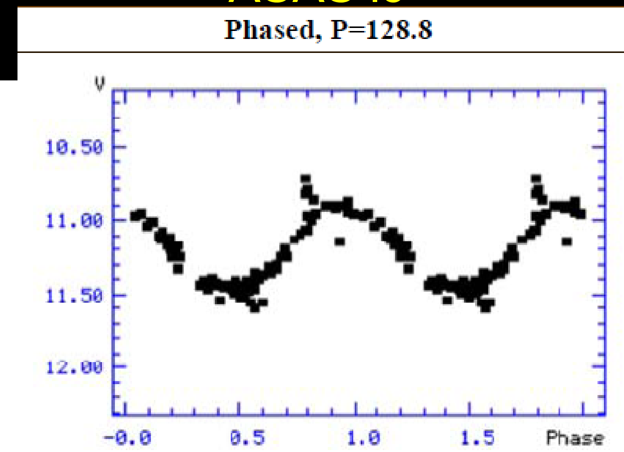


The most interesting ones are the ones that do not fit into common categories

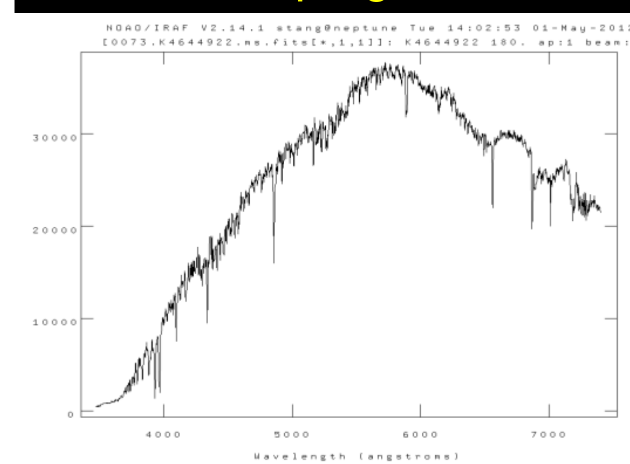
Probably a late-type or post AGB star, with a spectacular 60-yr dust ejection event
Very bright IR source, 0.5-2Jy at 10-50micron (IRAS)



ASAS Ic



FAST spectrum:
a G supergiant



Outline

- ❑ What I do: Introduction to DASCH
- ❑ How I do it: Photometry and Defect Filtering (*Tang et al. 2012c; Laycock, Tang, et al. 2010*)
- ❑ What I get - Scientific Results:
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Discovery of new type of variable stars: 3 unusual long-term K giant variables; ALL K2III

An unknown phase of evolution with dust production?

Tang et al. 2010, ApJL, 710, L77

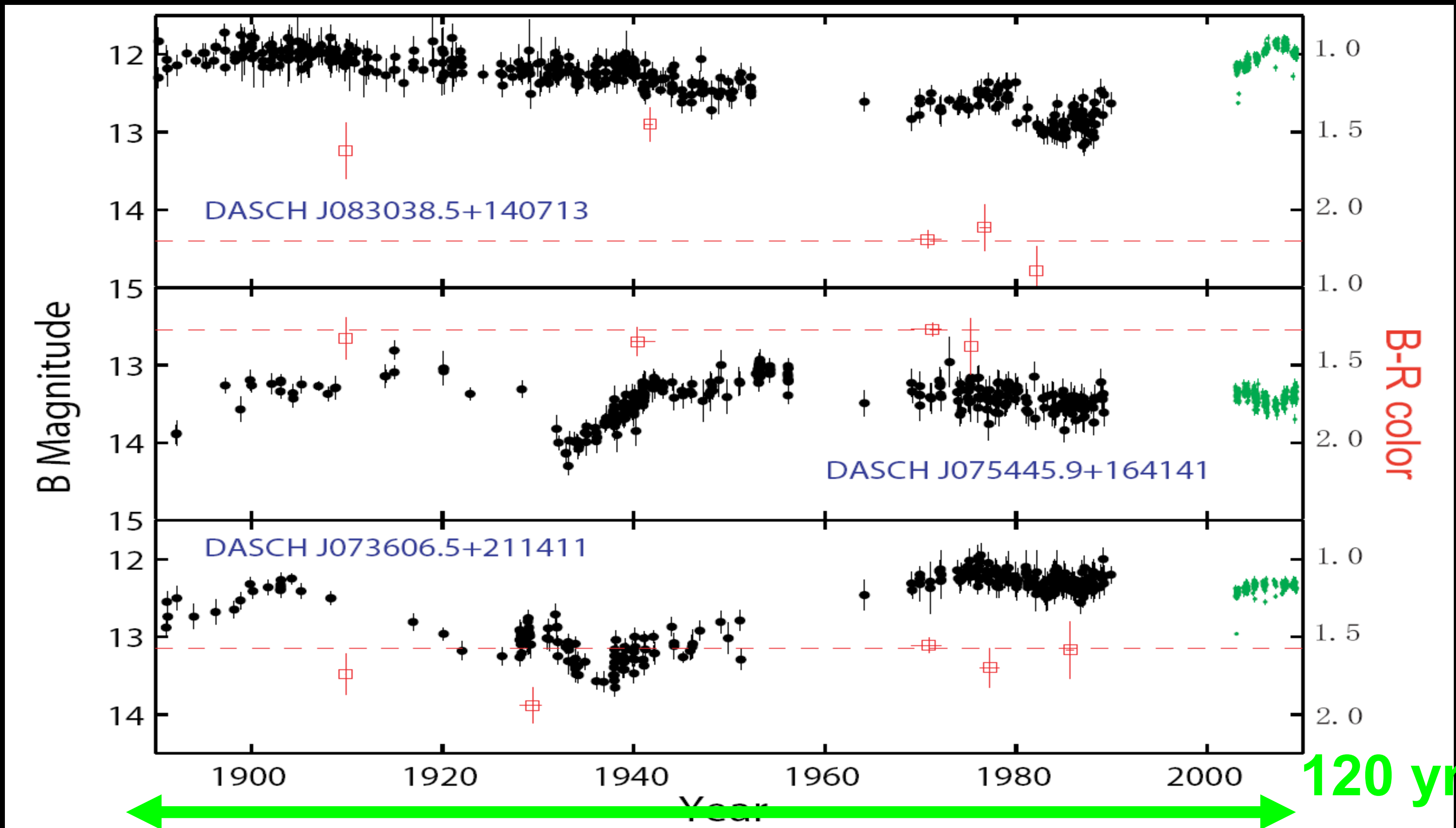
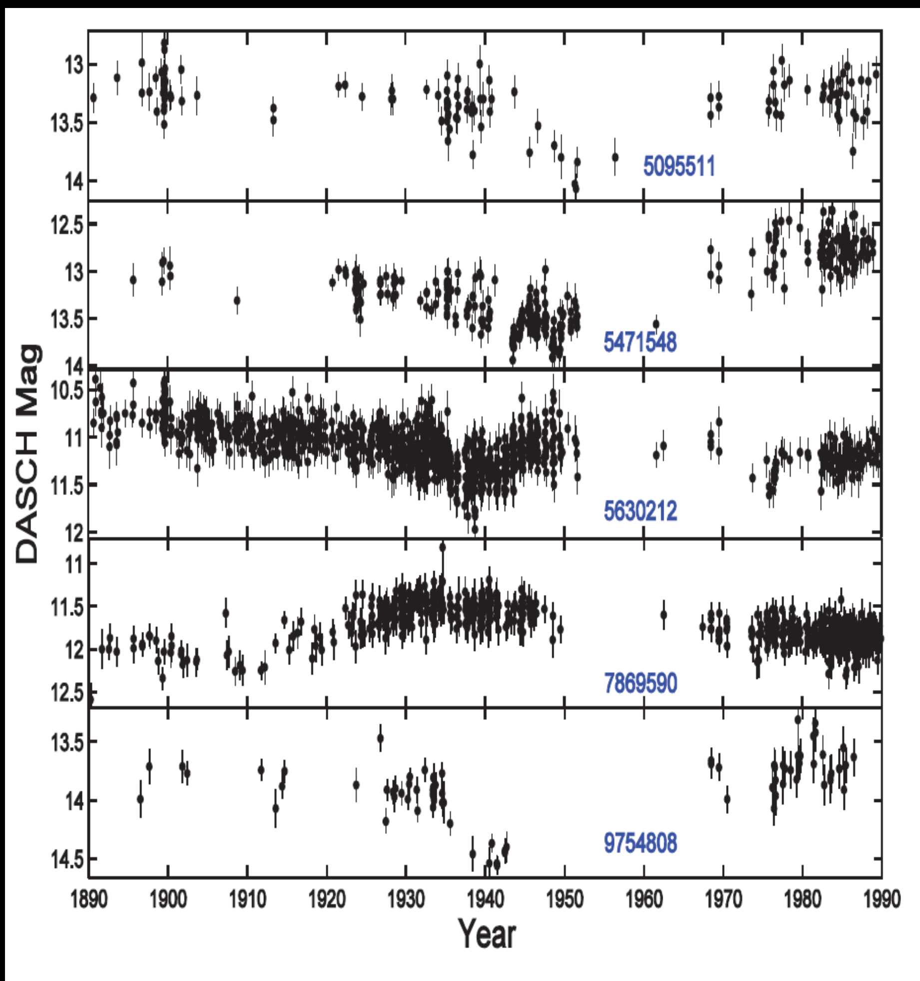


FIG. 1.— Lightcurves and color evolution of 3 unusual long-term variables which were found in DASCH scans near M44. Black dots with errorbars are the lightcurves from DASCH, small green dots are the lightcurves from ASAS. Since ASAS data are in V band, while DASCH magnitudes are blue, we added 1.16 mag to the ASAS V magnitudes in the plots which is the mean B-V value for K2III stars (Cox 2000). Red open squares are the B-R color derived from plates with y-axis labeled in the right, and red dashed lines mark the weighted mean B-R color values from 1970s to 1980s.

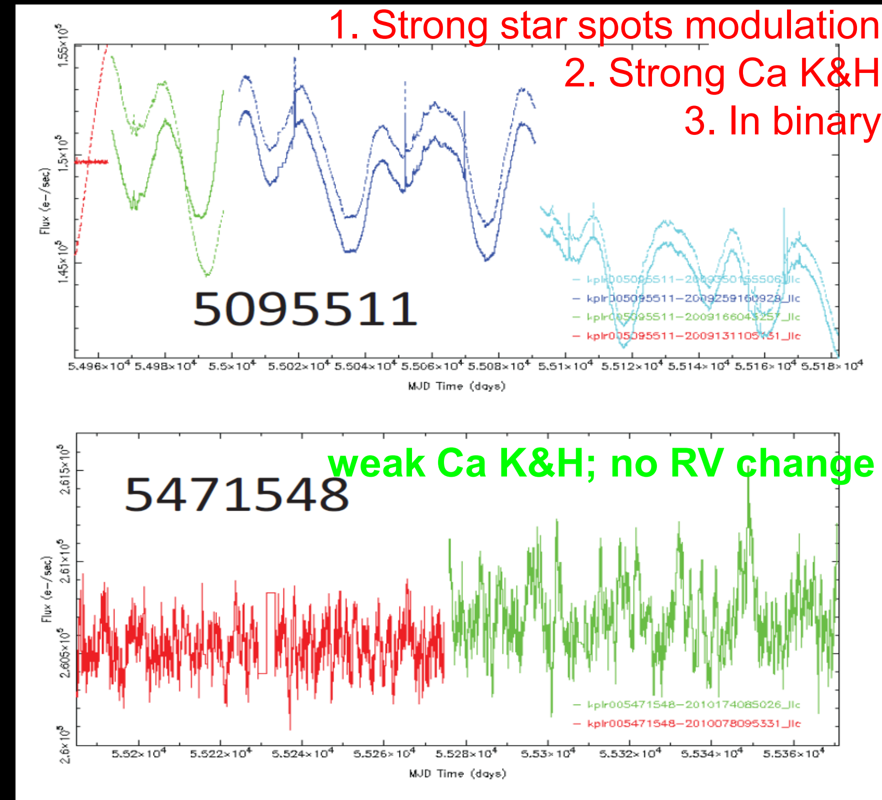
New K giants variables in the Kepler field

Tang et al. 2012c

DASCH light curves



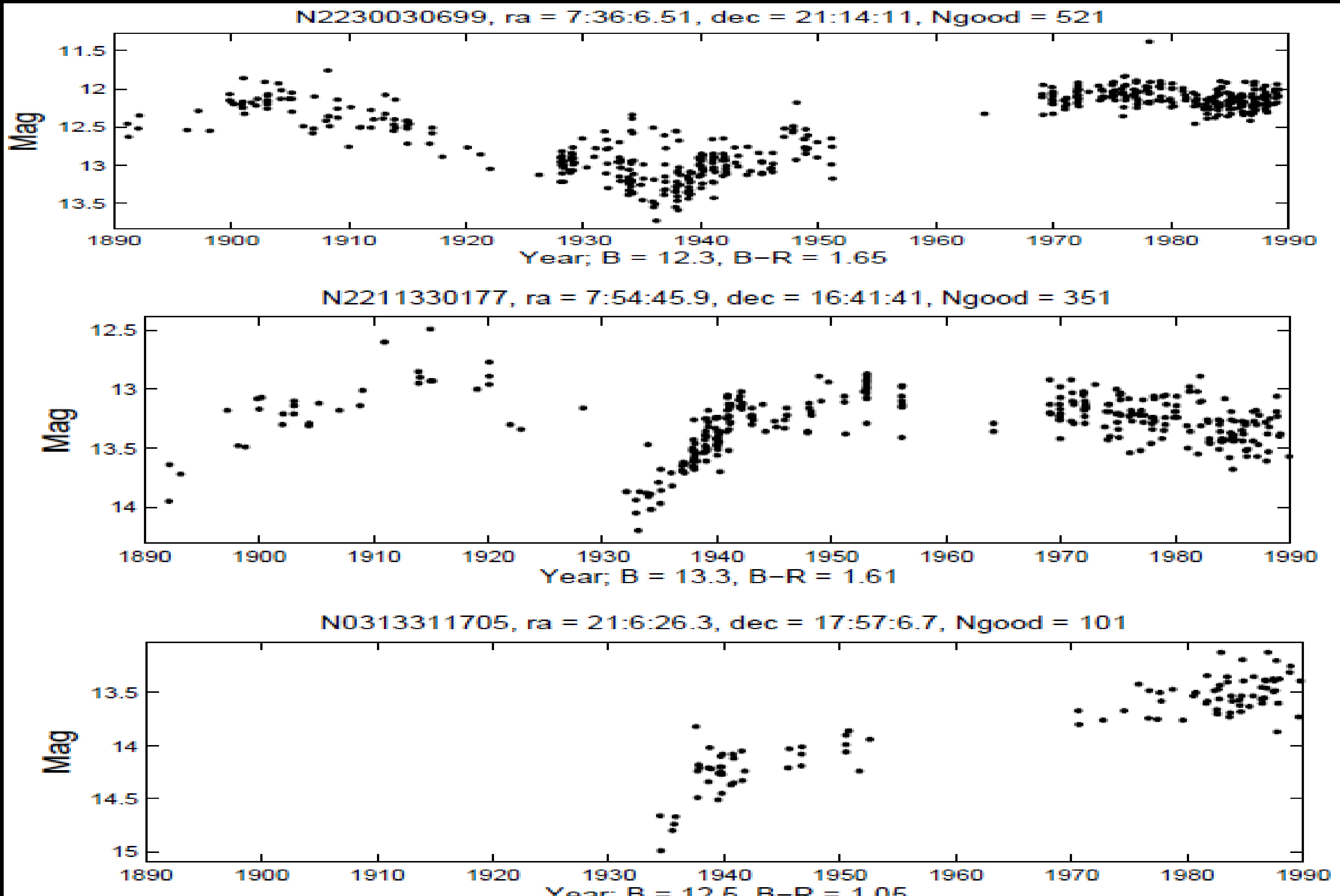
Kepler light curves



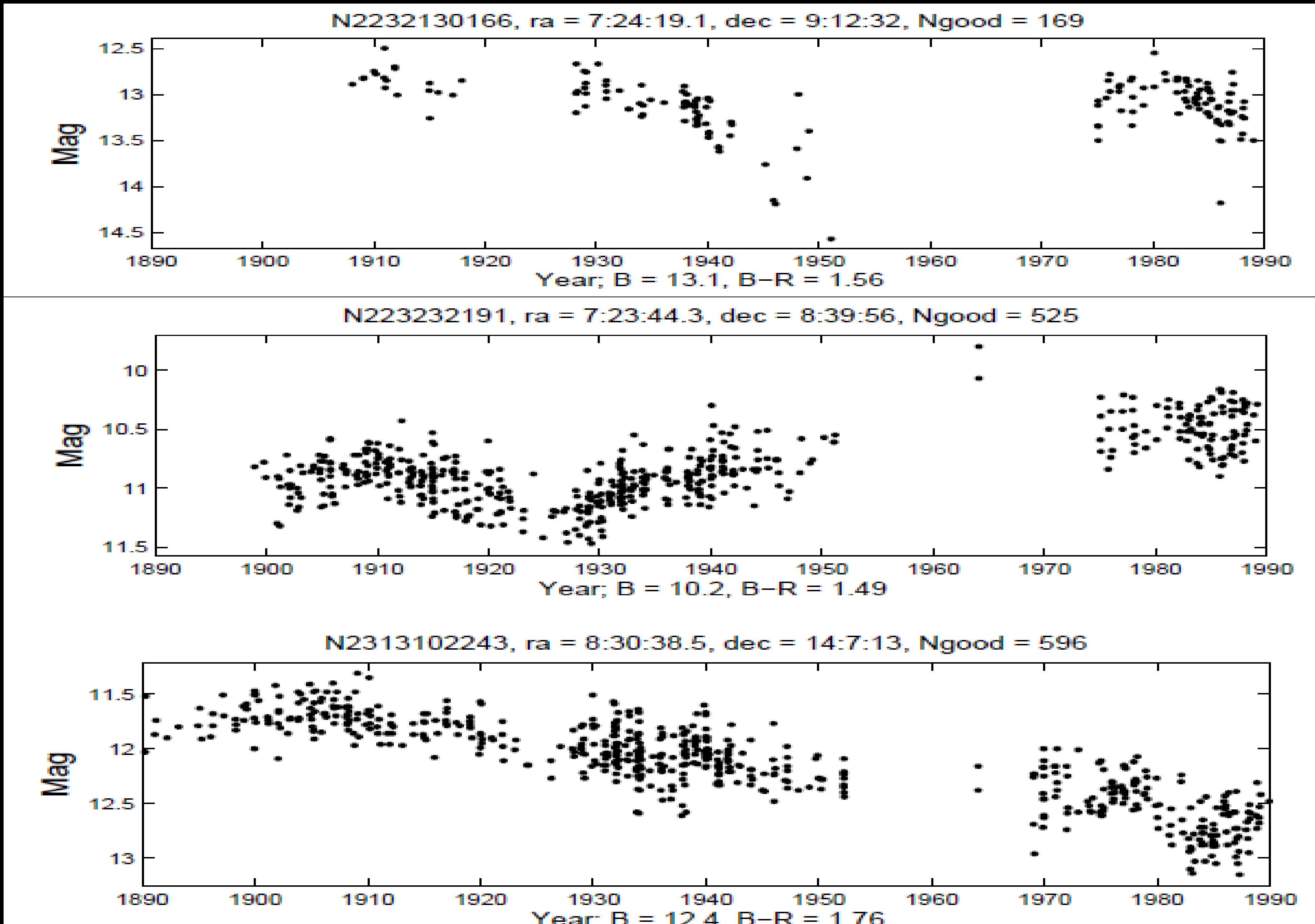
Probably a mix of two subgroups:

1. extreme RS CVn binaries with strong magnetic activities induced by binary interaction; variations may be related to ultra strong star spots activity.
2. Single stars; variations may be caused by novel dust formation processes during a certain evolutionary stage.

K giants in Binaries: Extreme RS CVns



Single K giant Stars: unknown dust processes?



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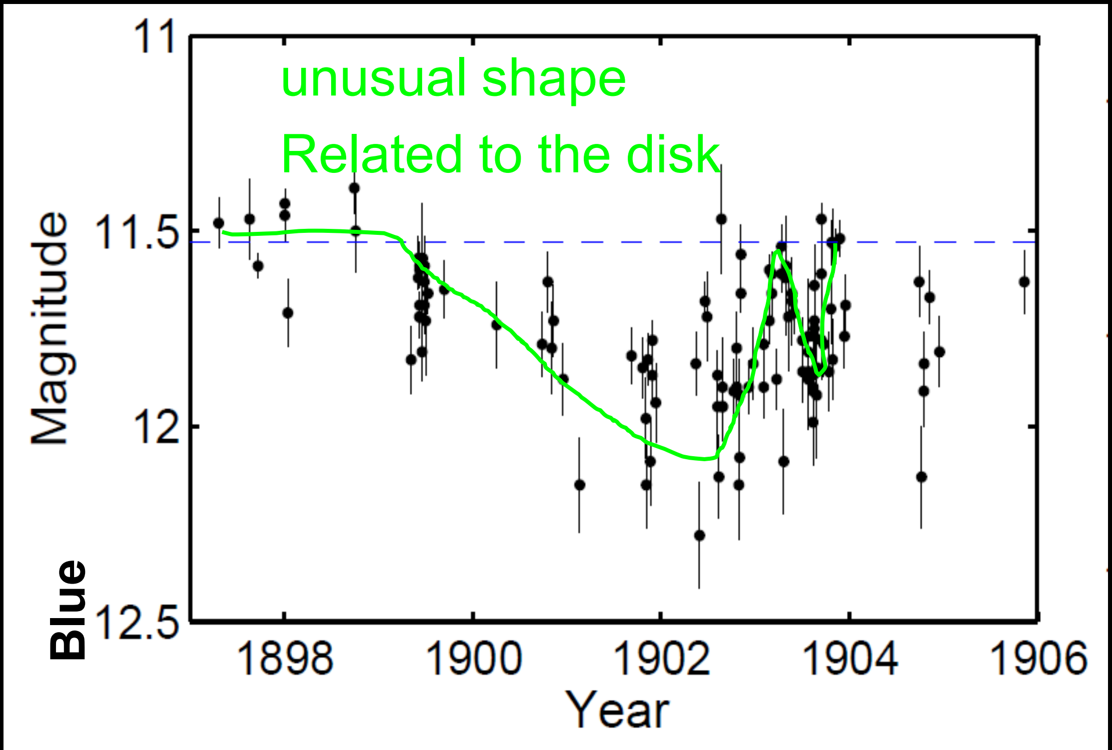
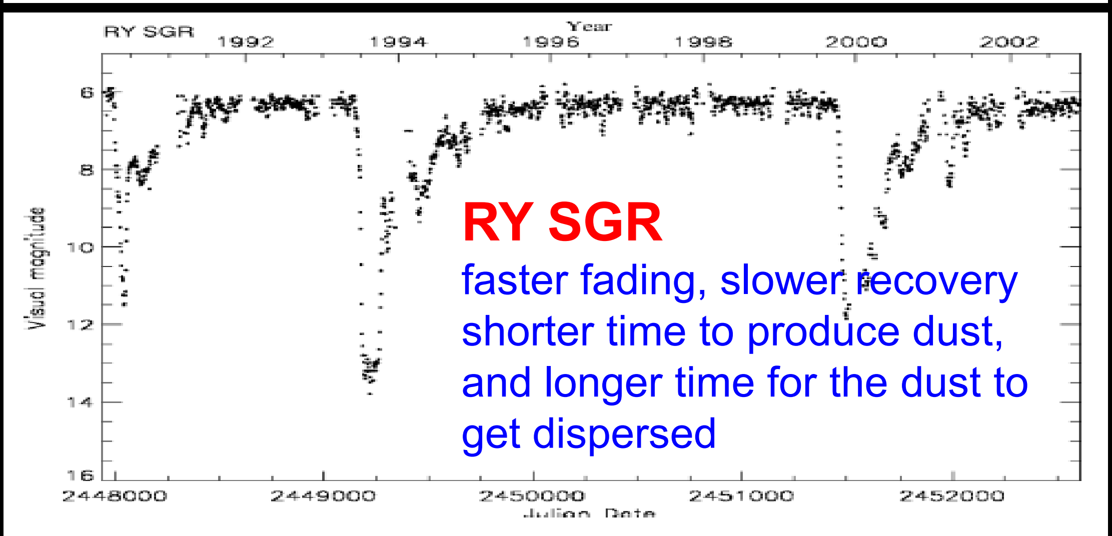
KU Cyg: 5-yr dust accretion event





Tang et al. 2011, ApJ, 738, 7

Algol-type eclipsing binary

3.85 $M_\odot$ F star + 0.48 $M_\odot$ K5III (*Smak & Plavec 1997*)

Slow Fading: accretion timescale

Increased mass transfer => increased disk mass => larger optical depth (dust extinction and neutral hydrogen scattering) => fading

Fast brightening:

Dust evaporates when moves closer to the F star => brightening

Fluctuations:

Dust condensation

Accretion energy release on the boundary layer

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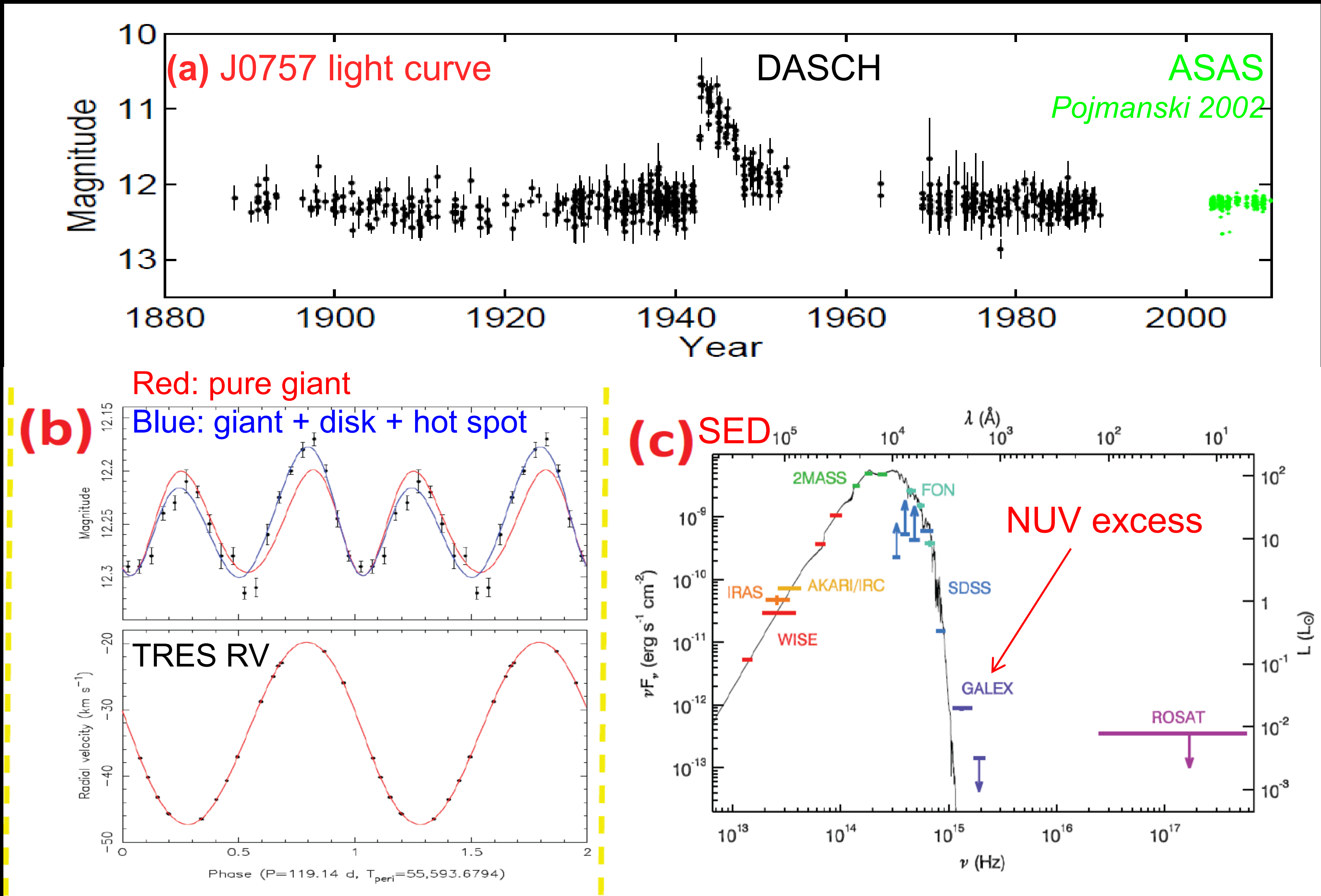
A peculiar 10-yr outburst

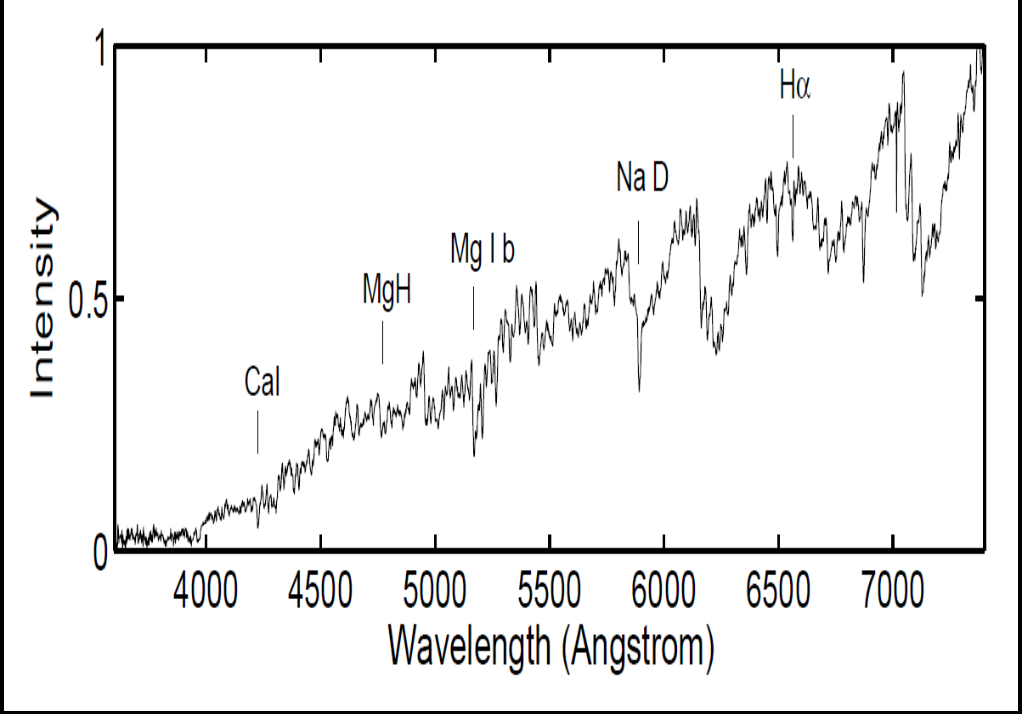
Tang et al. 2012a, ApJ, in press



DASCH J0757, list of properties:

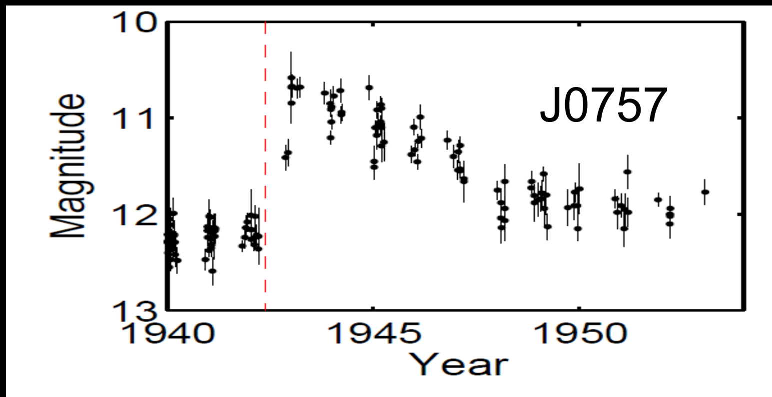
From atmosphere fitting, radial velocity & ellipsoidal variation

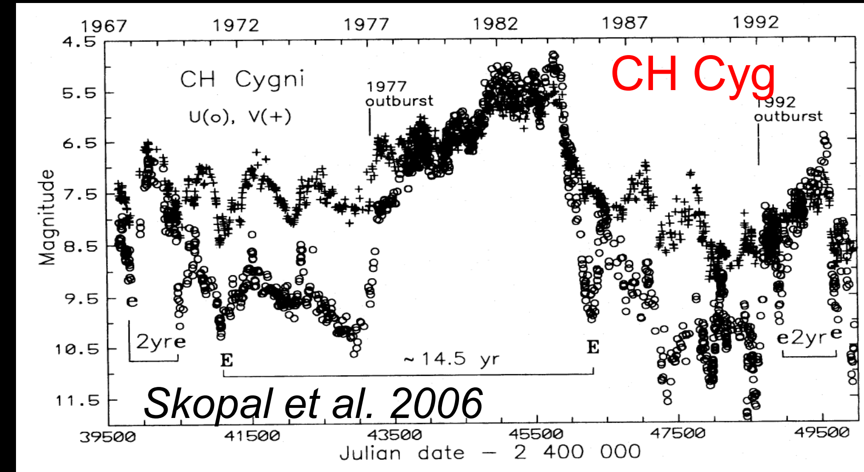
Spectra: normal M0 giant, no emission line

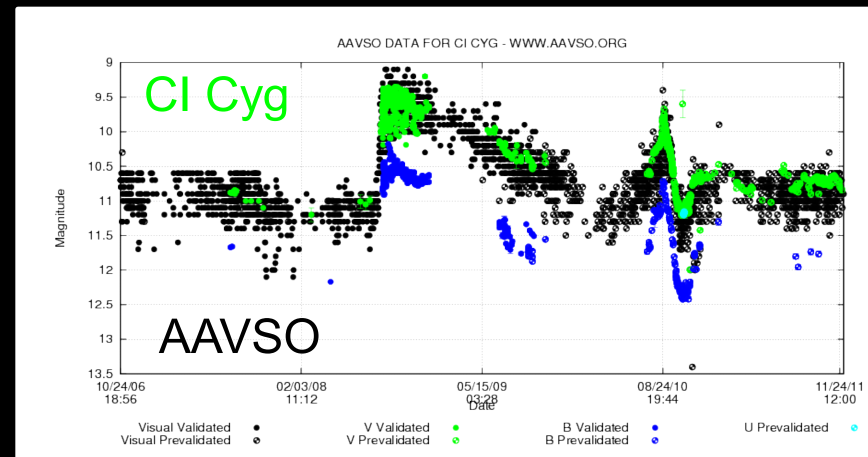


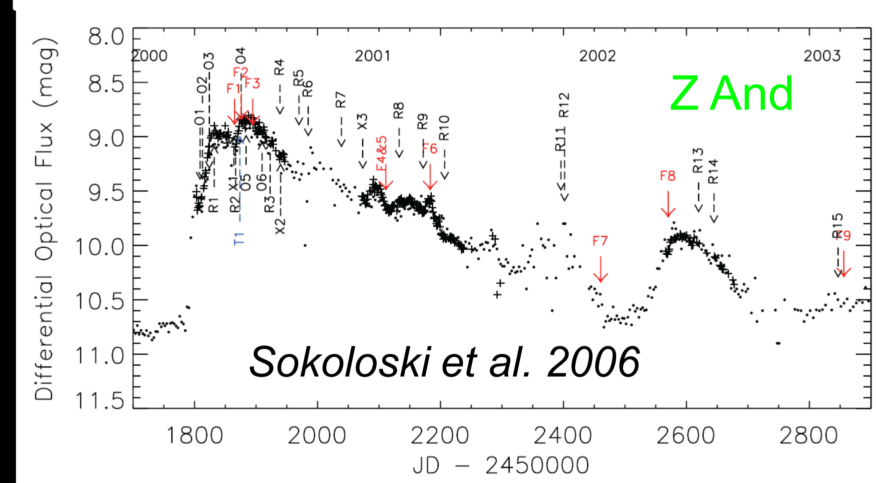
Spectral type	M0III
Orbital Period	119.18d+-0.07
Eccentricity	0.025+-0.01
M_giant	1-1.3 $M_\odot$
M_WD	~0.6 $M_\odot$
Distance	~1 kpc
L_giant	250 $L_\odot$
L_hot, quiescence Mdot	~2 $L_\odot$ 10^{-9} $M_\odot/yr$
M_B quiescence	~2
M_B outburst	~1
RL lobe filling factor	0.5-0.8

What powered the outburst?









- Accretion?

Light curve of J0757 doesn't look like the accretion powered systems, such as CH Cyg.

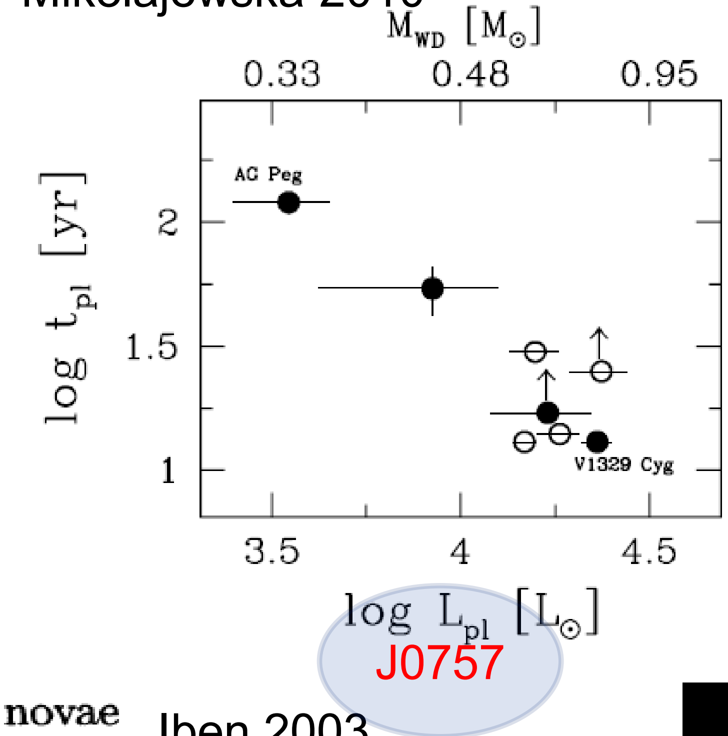
- Nuclear burning?

The outburst profile of J0757 more closely resembles that of Z And and CI Cyg, which are believed to have gone through nuclear burning powered outbursts (Mikolajewska 2003, et al. 2002). However, Z And and CI Cyg are hot and luminous during quiescence (H-burning in both quiescence & outburst).

Symbiotic novae?

- Symbiotic novae: thermonuclear runaways in symbiotic systems; only 9 symbiotic novae known so far (e.g. Kenyon 1986)
- Orbital period >2 yr, slow & quiet wind-accreting; strong emission lines
- Our object: period 119 days, NO emission lines, NO indication of wind or mass loss

Mikolajewska 2010



Iben 2003

Table 1. Observed properties of symbiotic novae

Star	Distance [kpc]	Period [yr]	$\dot{M}_{gw}$ (-7)	L_{pl} [$L_\odot$]	R_{max} [$R_\odot$]	τ^{red}_{obs} [yr]	τ^{blue}_{obs} [yr]
AG Peg	0.7	2.26	1.6	4000	18	60	50
V1329 Cyg	3.7	2.60	8	18 000	26	15	20
RT Ser	9.4	12.0	25	28 000	100	25	40
PU Vul	3.2	13.4	2.5	25 000	50	10	–
V1016 Cyg	3.9	> 15	130	36 000	6	0	> 40
HM Sge	2.9	> 15	100	28 000	20	4	> 20
RR Tel	2.6	> 15	50	17 500	110	7	> 30
RX Pup	1.8	200?	40	16 000	60	4	9

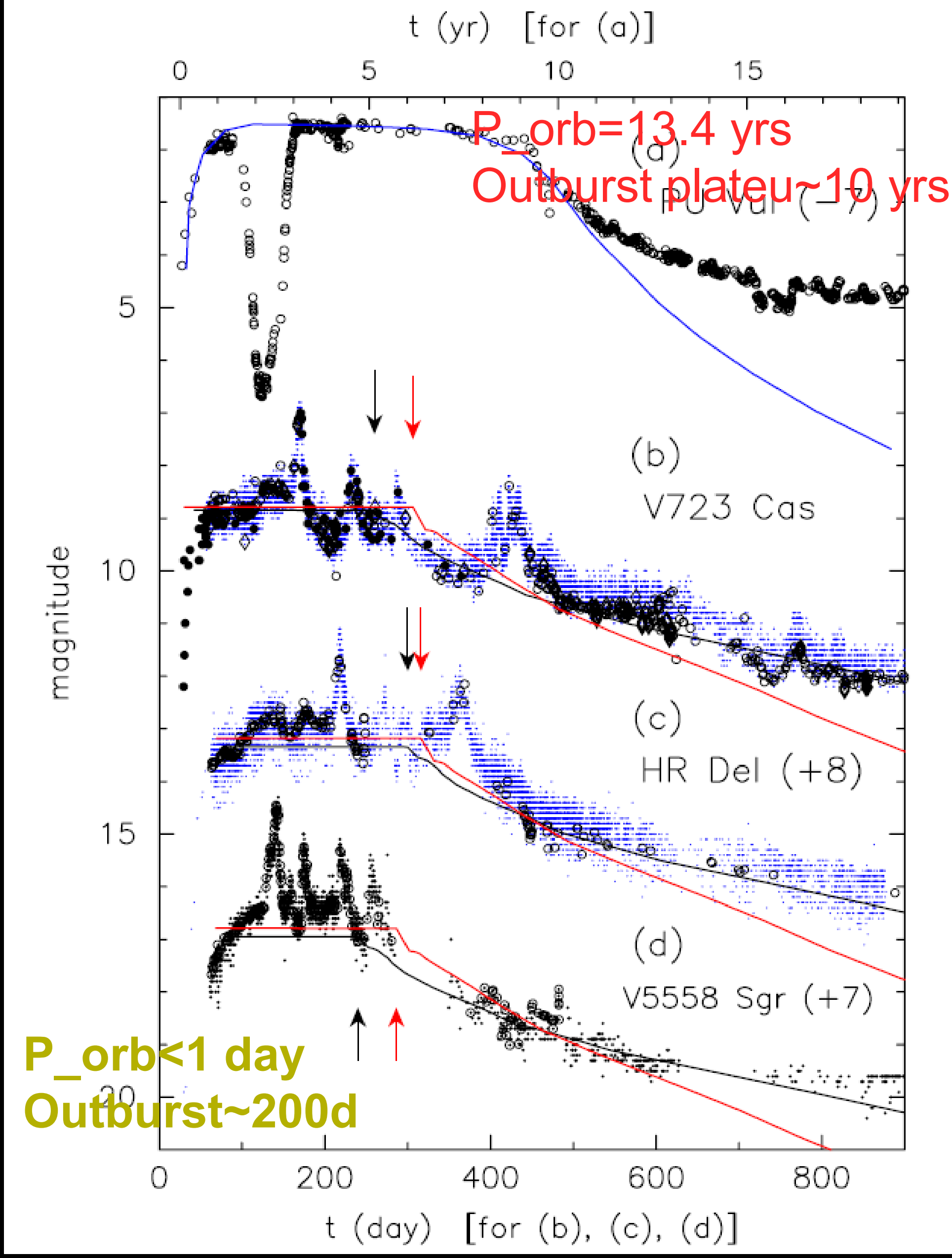
DASCH J0757 is a rare and new class of symbiotic variables:

A missing part of symbiotic family? Its current photometric and spectroscopic properties is not different from a normal red giant binary. It would not be picked out without the capture of its long outburst in 1940s on DASCH plates.

What sets the nuclear outburst timescale?

- Companion may play an important role (Kato & Hachisu 2011): a closer companion helps drive wind loss => shorter timescales
- With P=119 days, J0757 is at the valley between symbiotic novae (P>2 yr) and novae in close binaries (P<1 day)
- Missing class of possible SN Ia progenitors?

Kato & Hachisu (2011): all w/ 0.6 Msun WD



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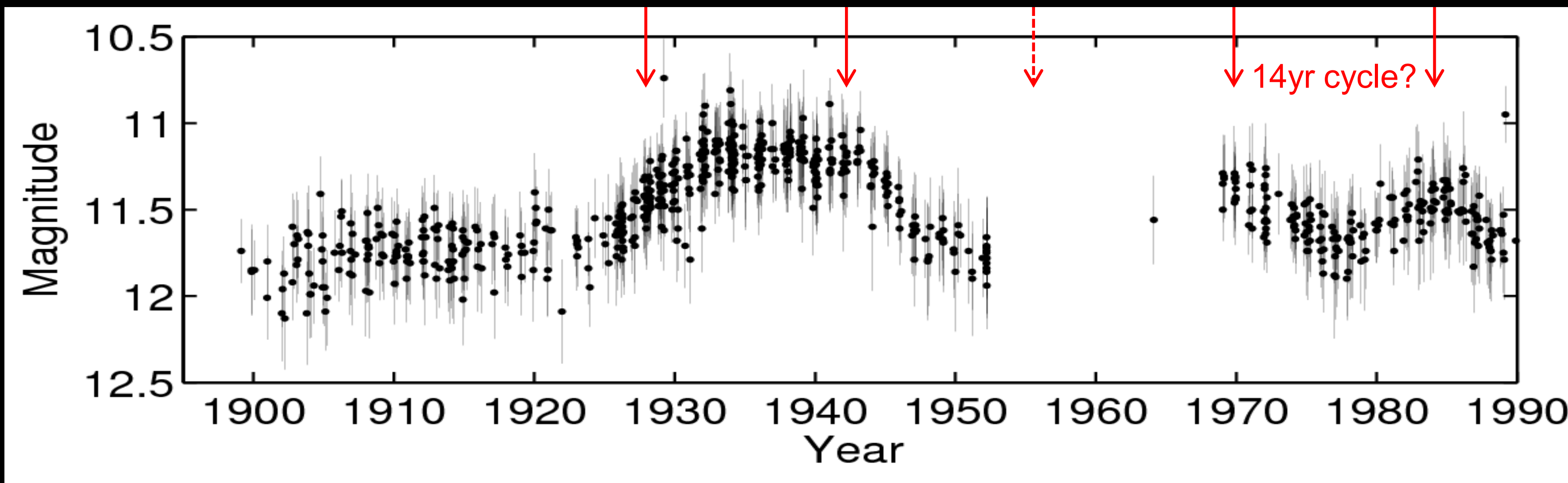
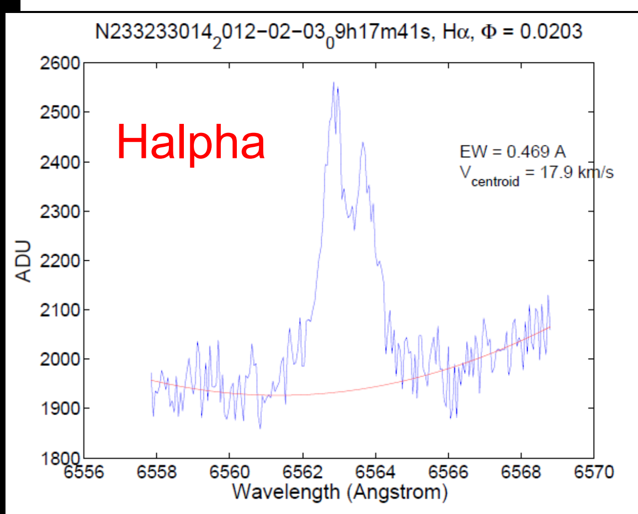
1st example: G8 dwarf binary with variations over decades

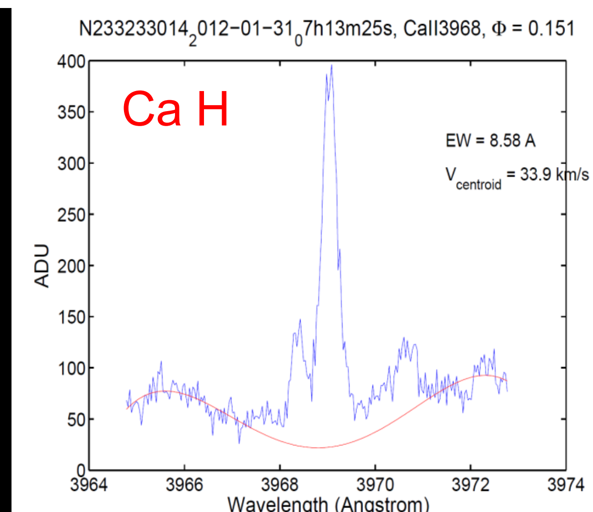
TRES spectra: Teff=5250+/-125, log(g)=4.50+/-0.25, Vrot=16+/-2, [m/H]=0.00+/-0.25

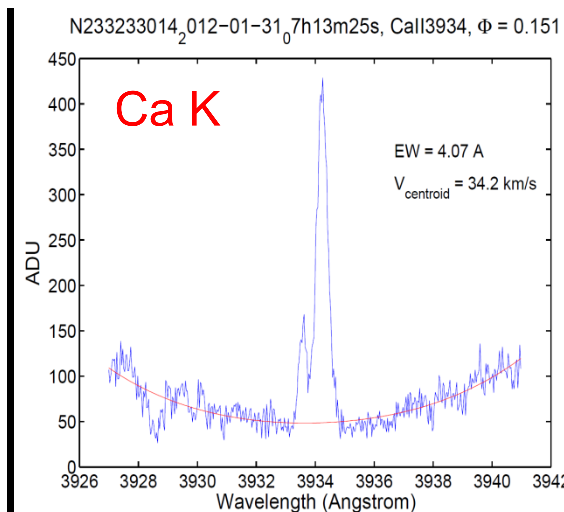
ROSAT source, 0.1 cts/s => L(0.1-2.4 keV)=4×10^{30} erg/s (Sun: $L_X \sim 10^{27}$-10^{28} erg/s)

Also a bright GALEX source, 10 times brighter than a normal G8V

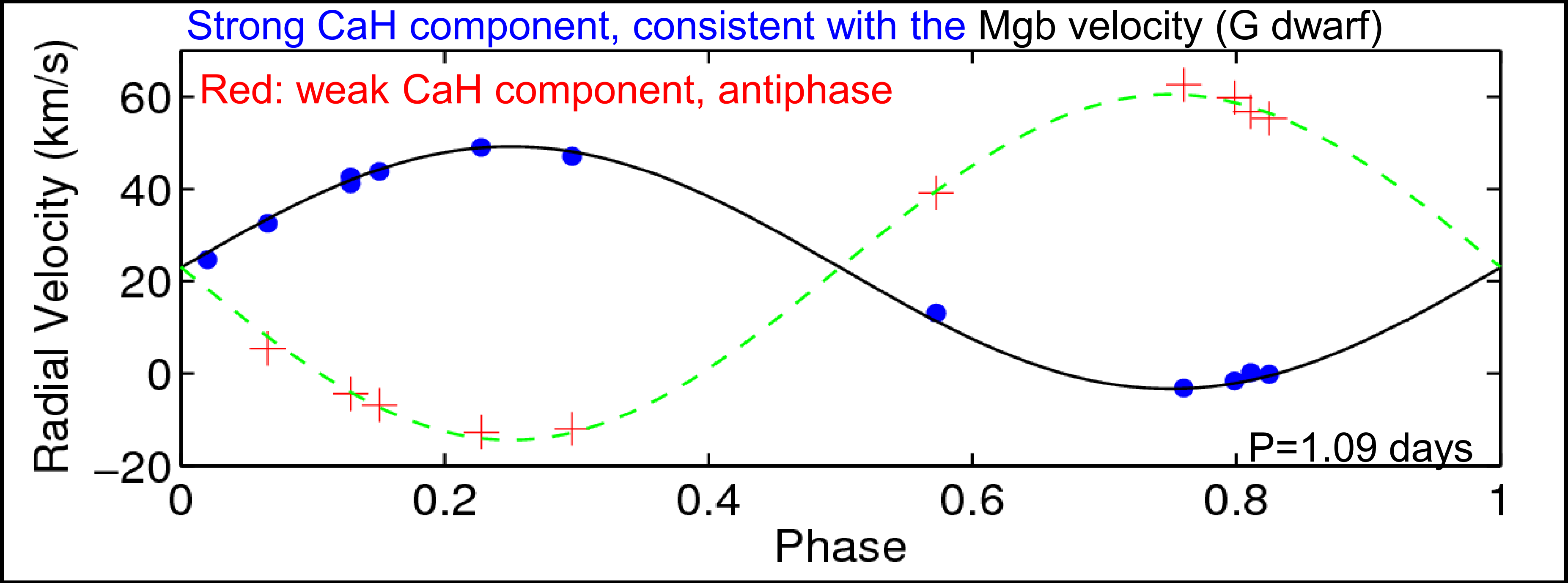








What is the companion & what powered the outbursts



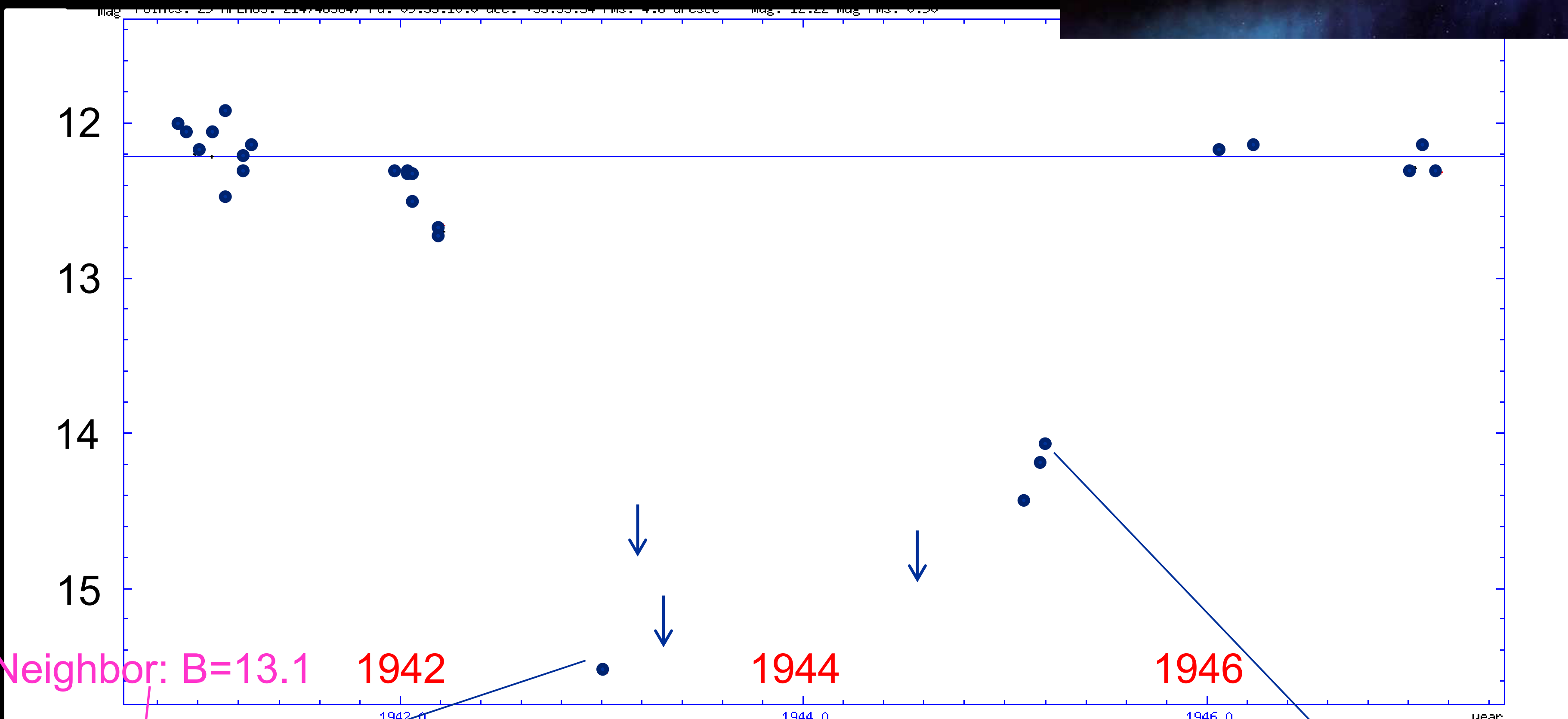
If the weak CaH&K component from the companion, then mass ratio: 1:0.67
G8V, M1 = 0.8-0.9 Msun, M2 = 0.5-0.6 Msun (most likely a WD)
⇒ a=2-2.1 Rsun; RL1=0.8-0.9 Rsun
⇒ The G dwarf is approximately Roche-lobe filling

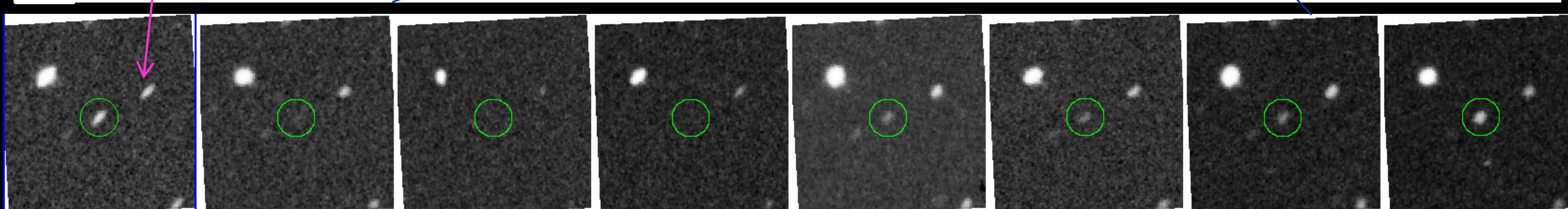
14-yr-cycle-like outbursts: As the G dwarf has very strong magnetic activity, it is natural to explain it as ‘solar cycle’ driven accretion on to a companion WD.

2nd example: ε Aurigae-like (8 AU disk)?

Eclipsed by a foreground cloud? 4yr x 10km/s = 8 AU

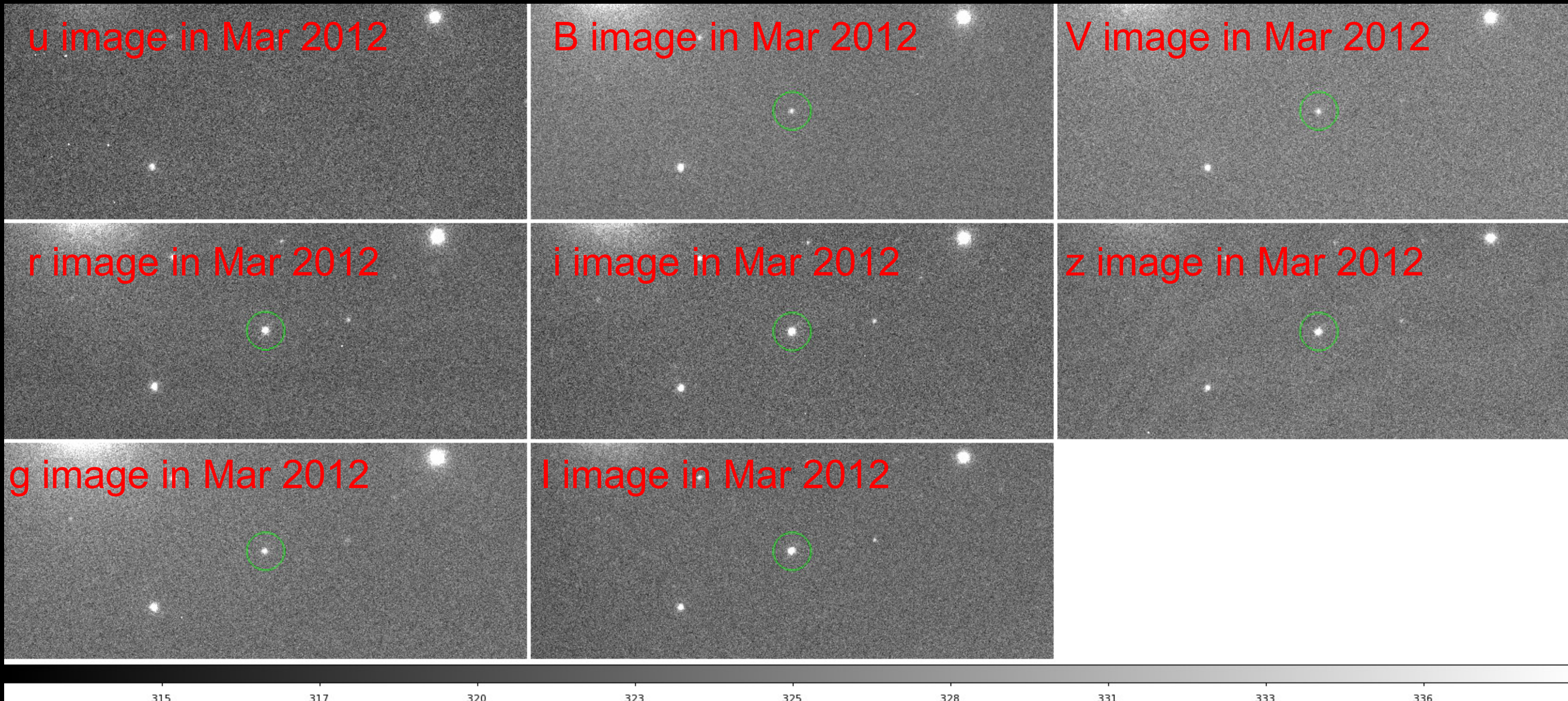
No significant 2MASS (JHK) & AKARI/IRC(9micron) flux excess

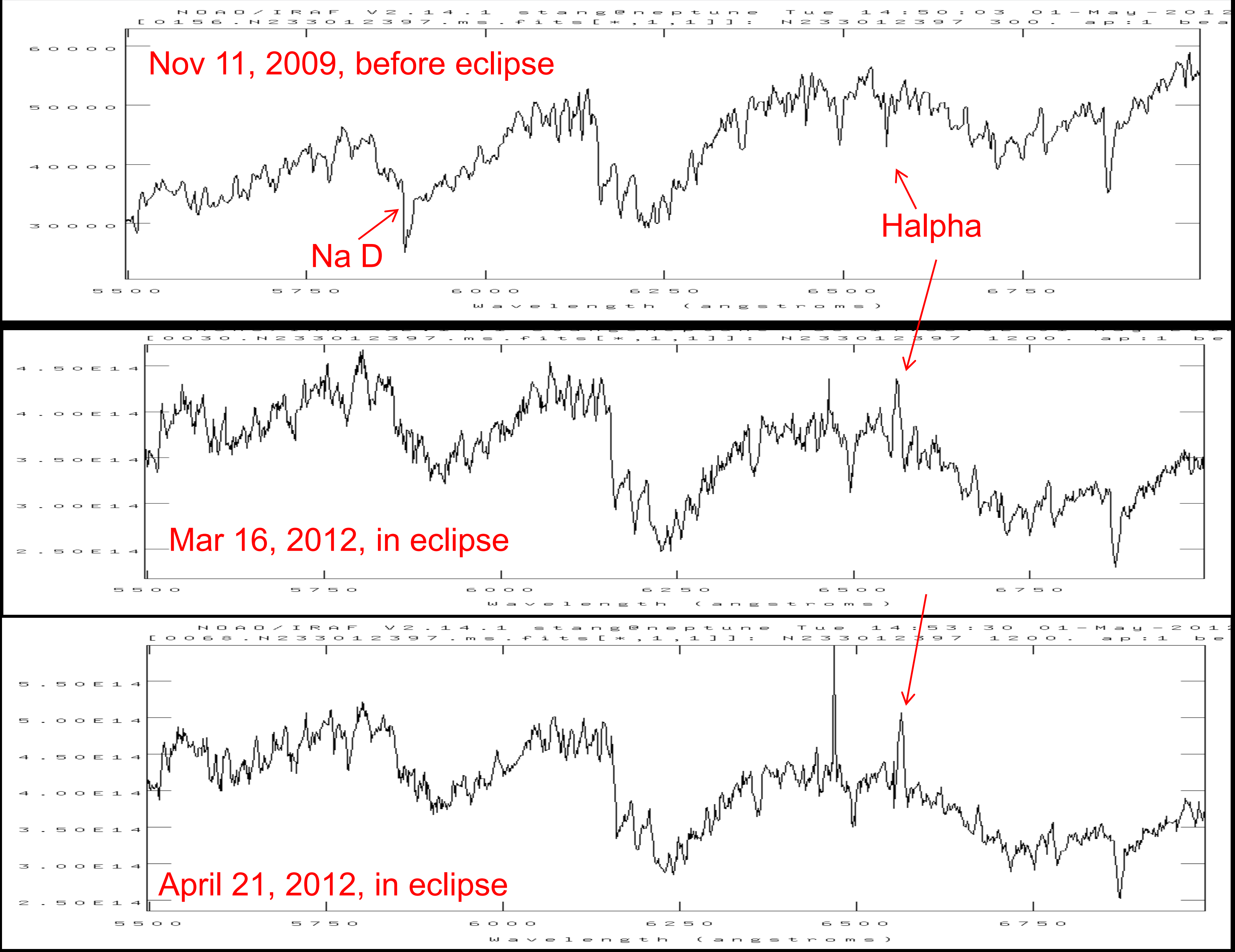




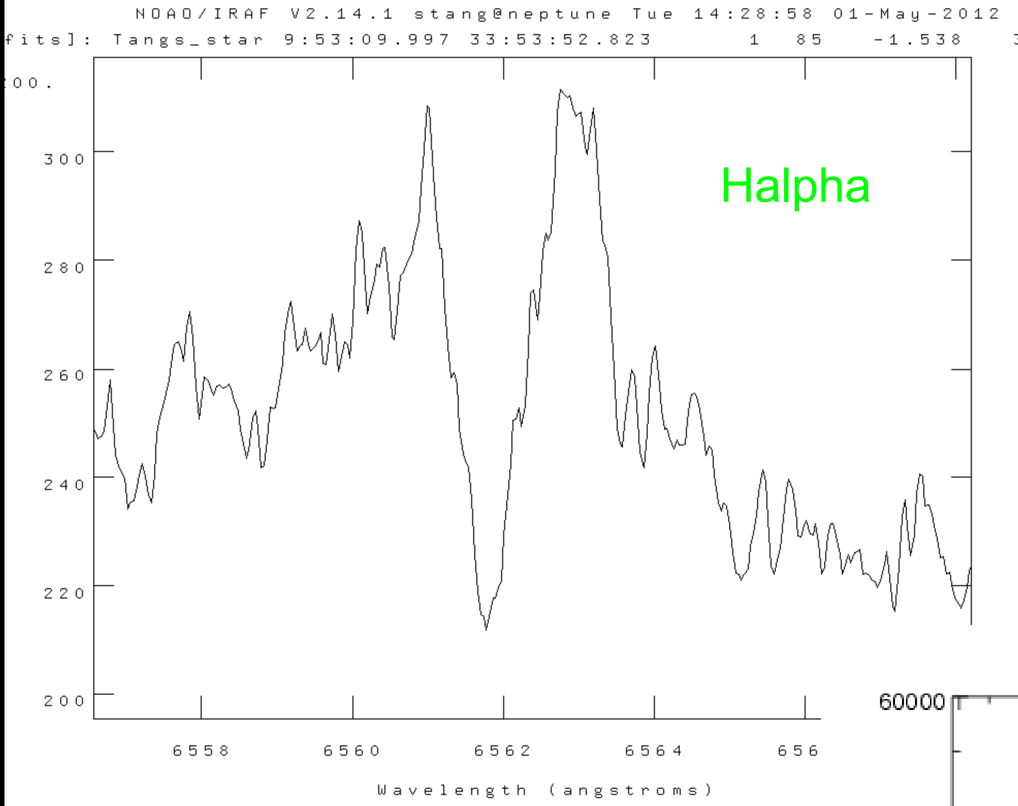
It is entering another eclipse now, 69 yrs after 1943, with ~4-4.5 mag dimming in optical (uBVgriz) and NIR (JHK) bands

=> solid body blocking, not dust extinction

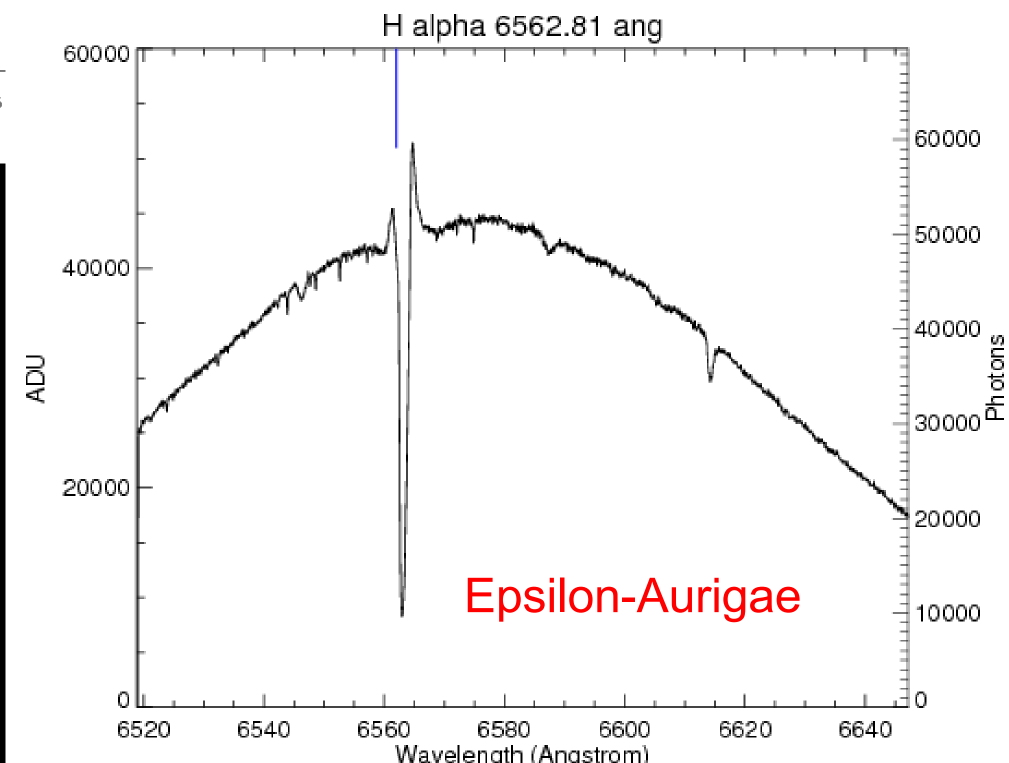




Nov 11, 2009, before eclipse
Na D
Halpha
Mar 16, 2012, in eclipse
April 21, 2012, in eclipse
NOAO/IRAF V2.14.1 stang@neptune Tue 14:50:03 01-May-2012
NOAO/IRAF V2.14.1 stang@neptune Tue 14:53:30 01-May-2012
5500
5750
6000
6250
6500
6750
wavelength (angstroms)
60000
50000
40000
30000
4.50E14
4.00E14
3.50E14
3.00E14
2.50E14
5.50E14
5.00E14



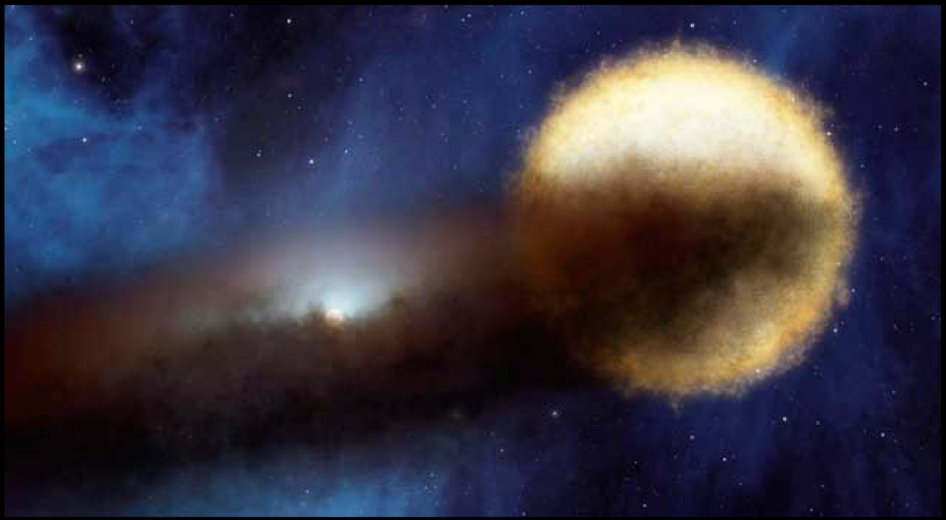
NOAO/IRAF V2.14.1 stang@neptune Tue 14:28:58 01-May-2012
fits]: Tangs_star 9:53:09.997 33:53:52.823 1 85 -1.538 3
Halpha
300
280
260
240
220
200
6558
6560
6562
6564
656
Wavelength (angstroms)



H alpha 6562.81 ang
Epsilon-Aurigae
ADU
Photons
60000
40000
20000
0
6520
6540
6560
6580
6600
6620
6640
Wavelength (Angstrom)

What causes the eclipses?

- Two eclipses: 1943-1946; 2012-?
- Coverage from 1890-1950 & 1970-1990: period = 69/N, N>1 is ruled out => P=69yr
- Similar change in optical and NIR bands => solid body blocking, not dust extinction
- What causes 3yr solid body blockings in a P=69yr binary?
- A companion with a huge disk
- Where is the disk come from?
- It is a M0III star, not a huge-mass-loss late AGB star; no mechanism to provide mass loss to form a disk for its companion
- It is a M0III star, not a young object, its companion is unlikely to have a protoplanetary disk



Summary

- Development of DASCH photometry and variable search
  - Photometry achieved 0.1-0.13 mag: photometric calibration, color-term fitting, defect filtering and local calibrations using neighbor stars with similar magnitudes (*Tang et al. 2012c; Laycock, Tang, et al. 2010, AJ*)
  - Kepler Planet Host Stars: No variations found (*Tang et al. 2012b, AJ, submitted*)
  - Variable Search and Catalog: effectively found most large amplitude variables (RMS>0.25 mag) (*Tang et al. 2012d*)
- Study long-term variables using DASCH data, archive data & spectroscopic follow-up observations
  - Peculiar K Giant Variables with ~1 mag variations over decades: provide new insights into dust formation processes or extreme magnetic activities on stars (*Tang et al. 2010, ApJL; 2012e*)
  - A 5-yr dust-accretion event in KU Cyg: first evidence of dust transportation and evaporation in an accretion disk (*Tang et al. 2011, ApJ*)
  - A 10-yr Nova-like outburst in a peculiar symbiotic system, may be powered by nuclear burning without significant mass loss and thus the WD could grow. (*Tang et al. 2012a, ApJ, in press*)
- Ongoing work: hundreds of variables; a few dozen of them do not belong to any common class - stay tuned