Pulsating Variable Stars in the NASA *Kepler* 2 Mission

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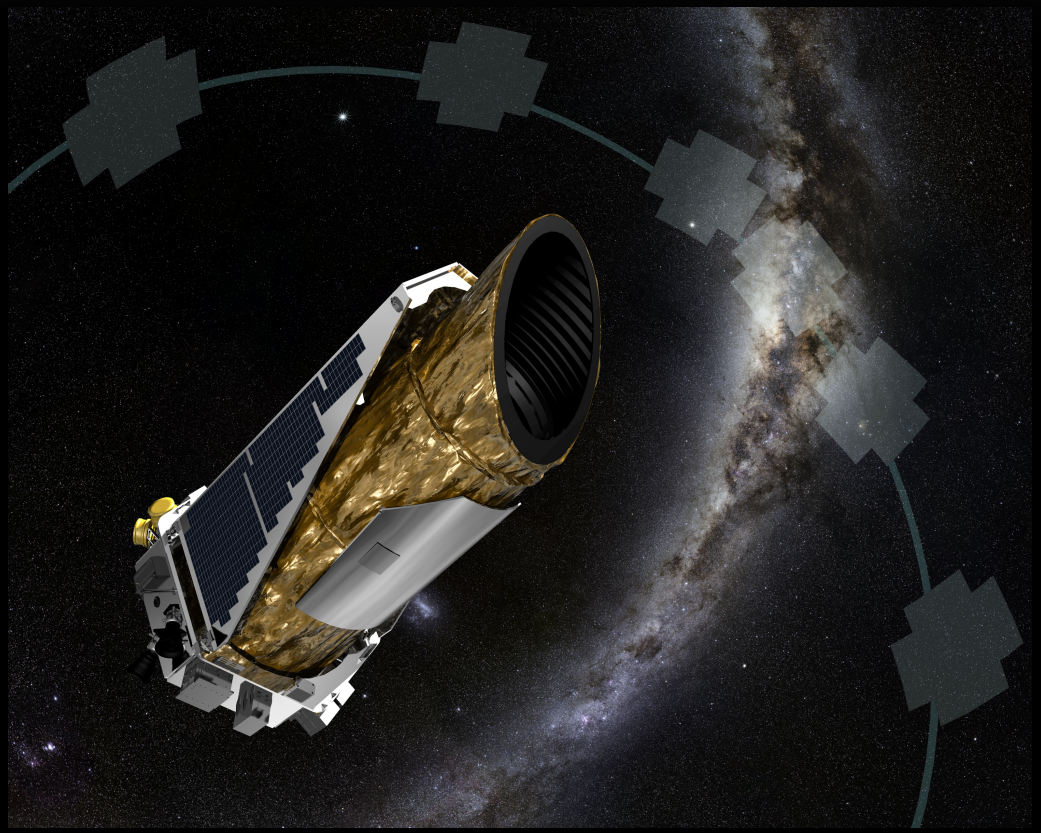


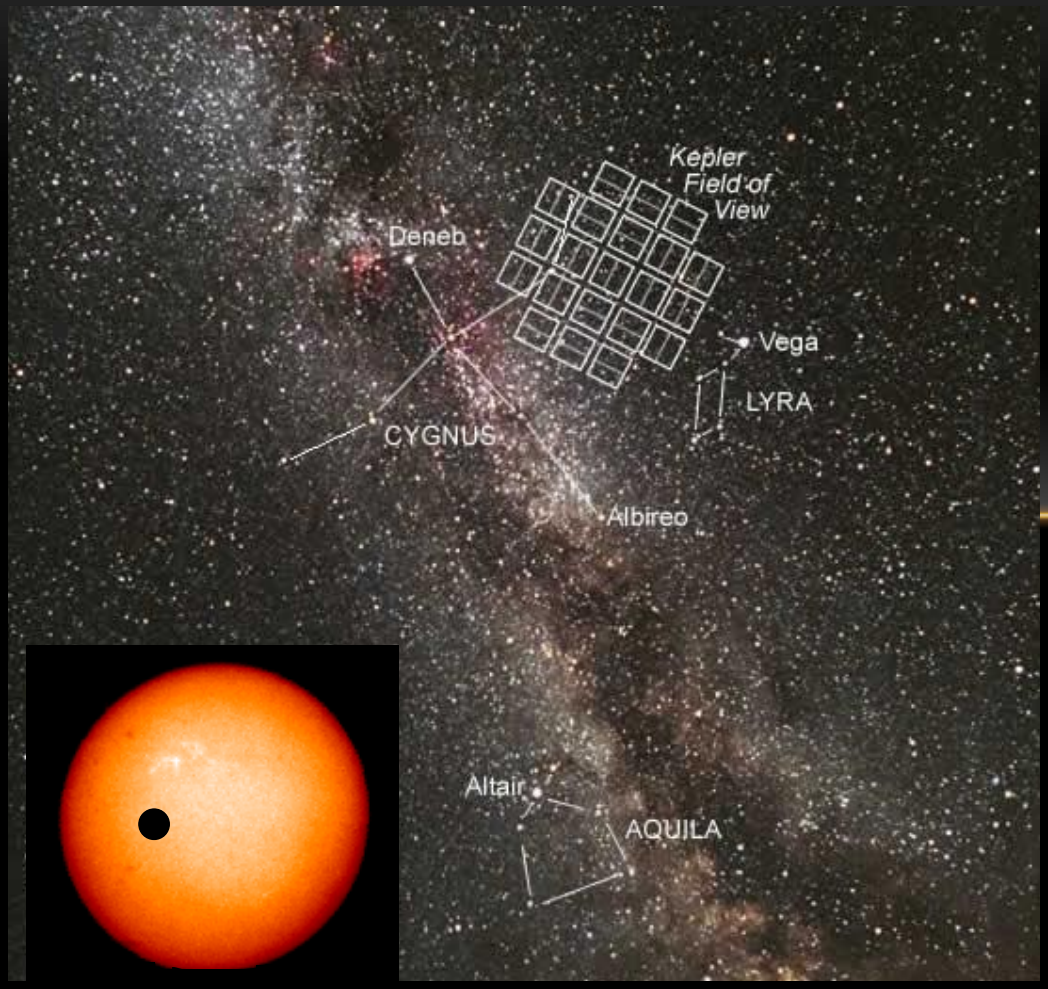
http://kepler.nasa.gov

LA-UR-18-30440

Abstract

The NASA *Kepler* spacecraft launched nearly 10 years ago has been observing fields along the ecliptic plane for about 90 days each to detect planets and monitor stellar variability. We analyzed the light curves of thousands of main-sequence stars observed as part of the *Kepler* Guest Observer program. Here we summarize the statistics of discovery and properties of the pulsation amplitude spectra for about 250 delta Scuti variable stars found in *Kepler 2* Campaigns 4 through 17. These stars are about twice as massive as the Sun, pulsating in many simultaneous radial and nonradial pulsation modes, with periods of about two hours. We discuss the potential and challenges for these stars of using pulsations to constrain stellar interior properties.

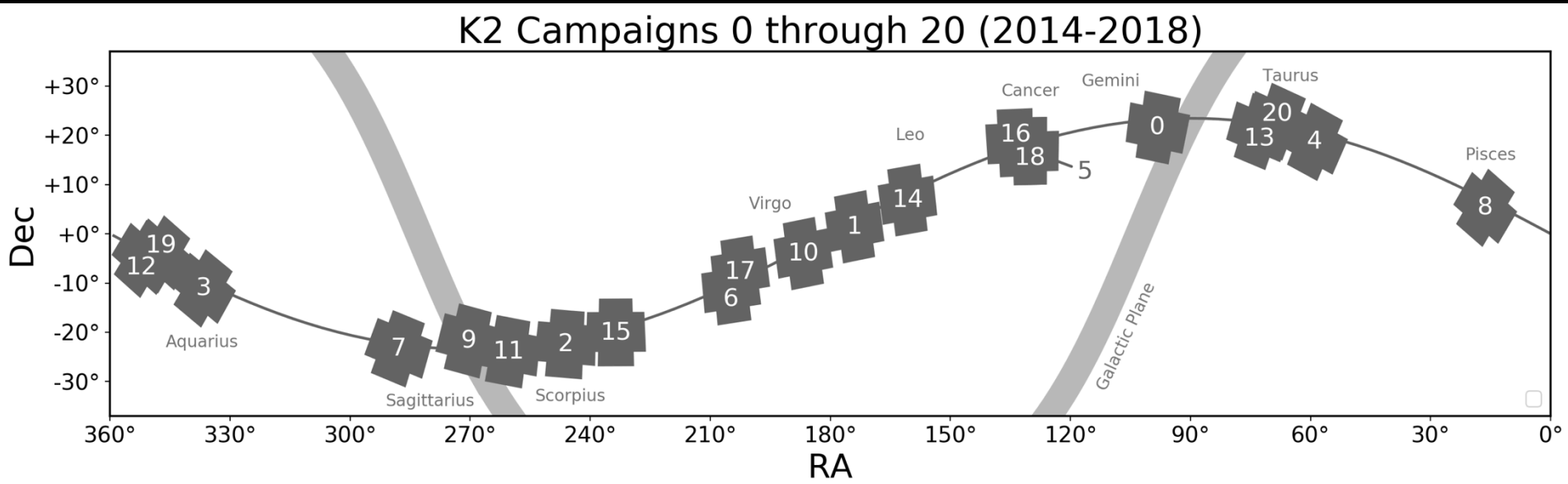
The NASA *Kepler* Mission



- Launched March 6, 2009
- Main goal was to search for exoplanets in habitable zone
- High-precision CCD photometry to detect planetary transits
- Secondary mission to survey and monitor variability of stars for *asteroseismology*

http://kepler.nasa.gov

After failure of 2nd out of 4 reaction wheels, K2 mission observed 19 new fields along ecliptic plane for up to ~80 days each



November 15 update: On Thursday evening, NASA's Kepler space telescope received its final set of commands to disconnect communications with Earth. The "goodnight" commands finalize the spacecraft's transition into retirement, which began on Oct. 30 with NASA's announcement that Kepler had run out of fuel and could no longer conduct science. Coincidentally, Kepler's "goodnight" coincides with the anniversary of the death of its namesake, German astronomer Johannes Kepler, who discovered the laws of planetary motion and died 388 years ago on Nov. 15, 1630.

Some properties of delta Scuti variables

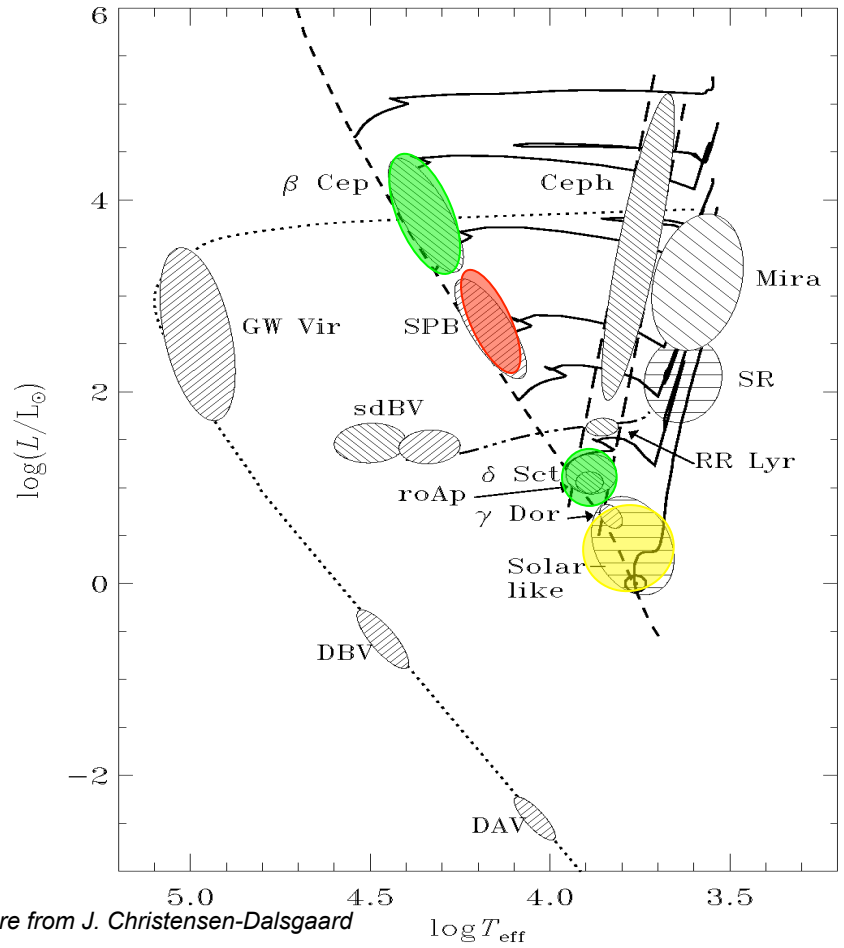
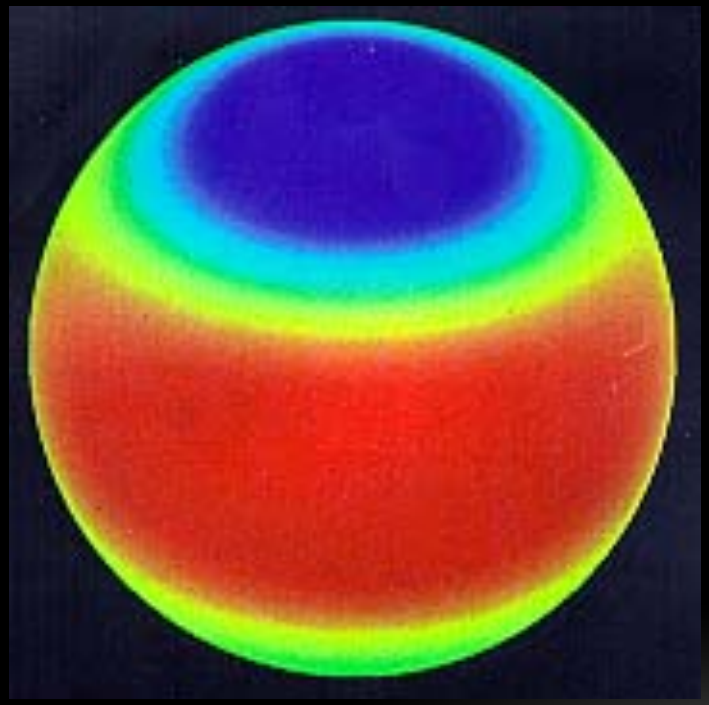


Figure from J. Christensen-Dalsgaard

- Main-sequence stars (core or shell hydrogen-burning)
- Pulsate in many simultaneous radial and nonradial modes
- Pulsation periods of about 2 hours
- Mass about 2 solar masses
- Effective temperature about 7000 K
- Convective cores

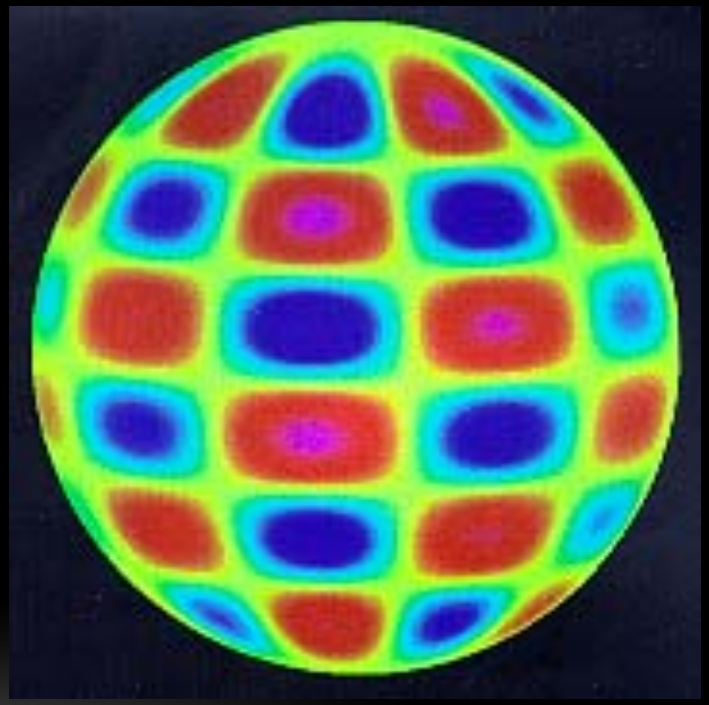
K. Pollard 2009

Kepler photometry can detect radial and low-degree nonradial pulsation modes in which the variations do not average out over the unresolved disk



Nonradial *l*=2 *m=0 mode*

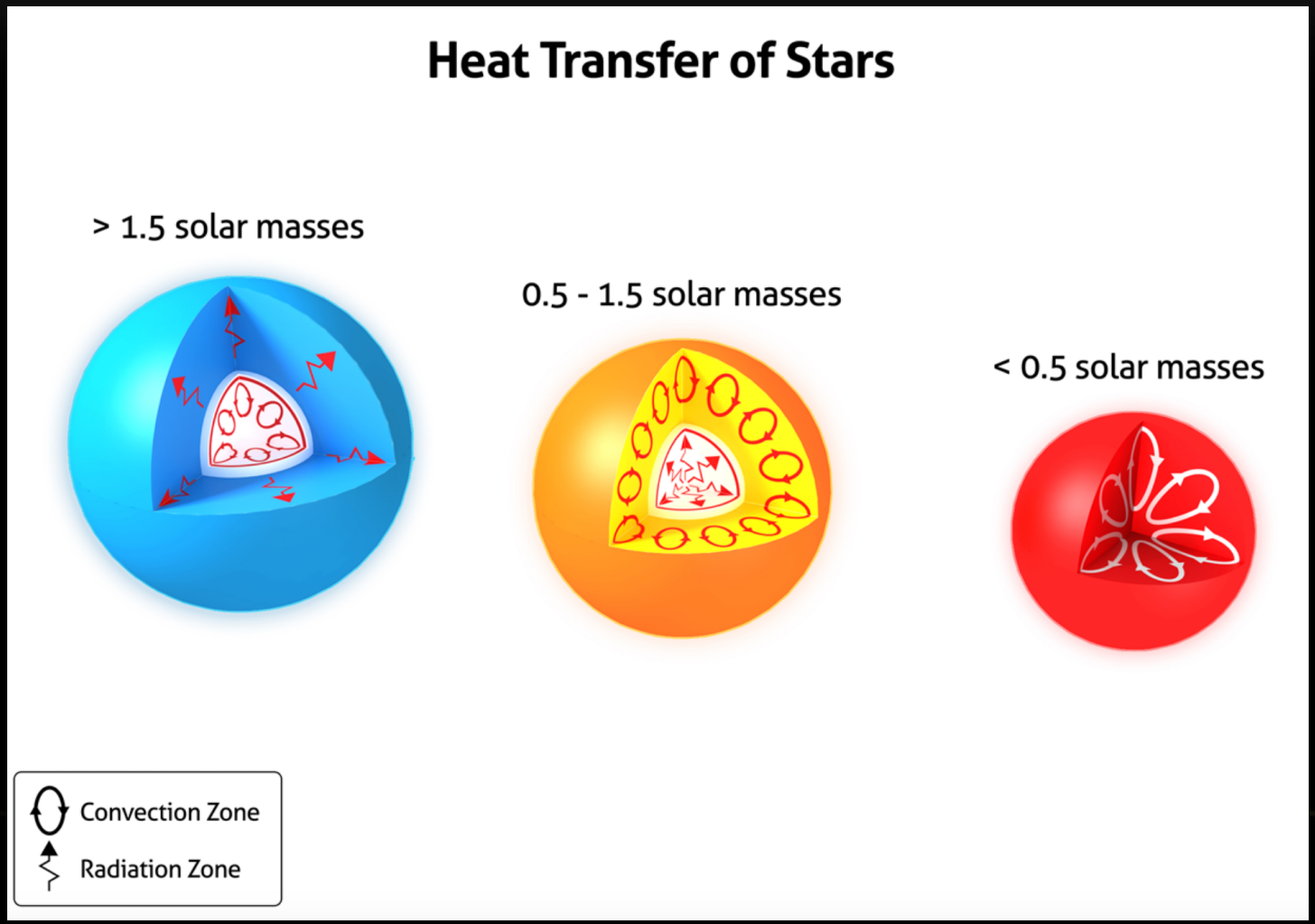
(observable)



Nonradial l=10 m=5 mode

(probably not observable)

While sun-like stars have convective envelopes and radiative cores, delta Scuti variables have convective cores and radiative envelopes



Why study delta Scuti stars?

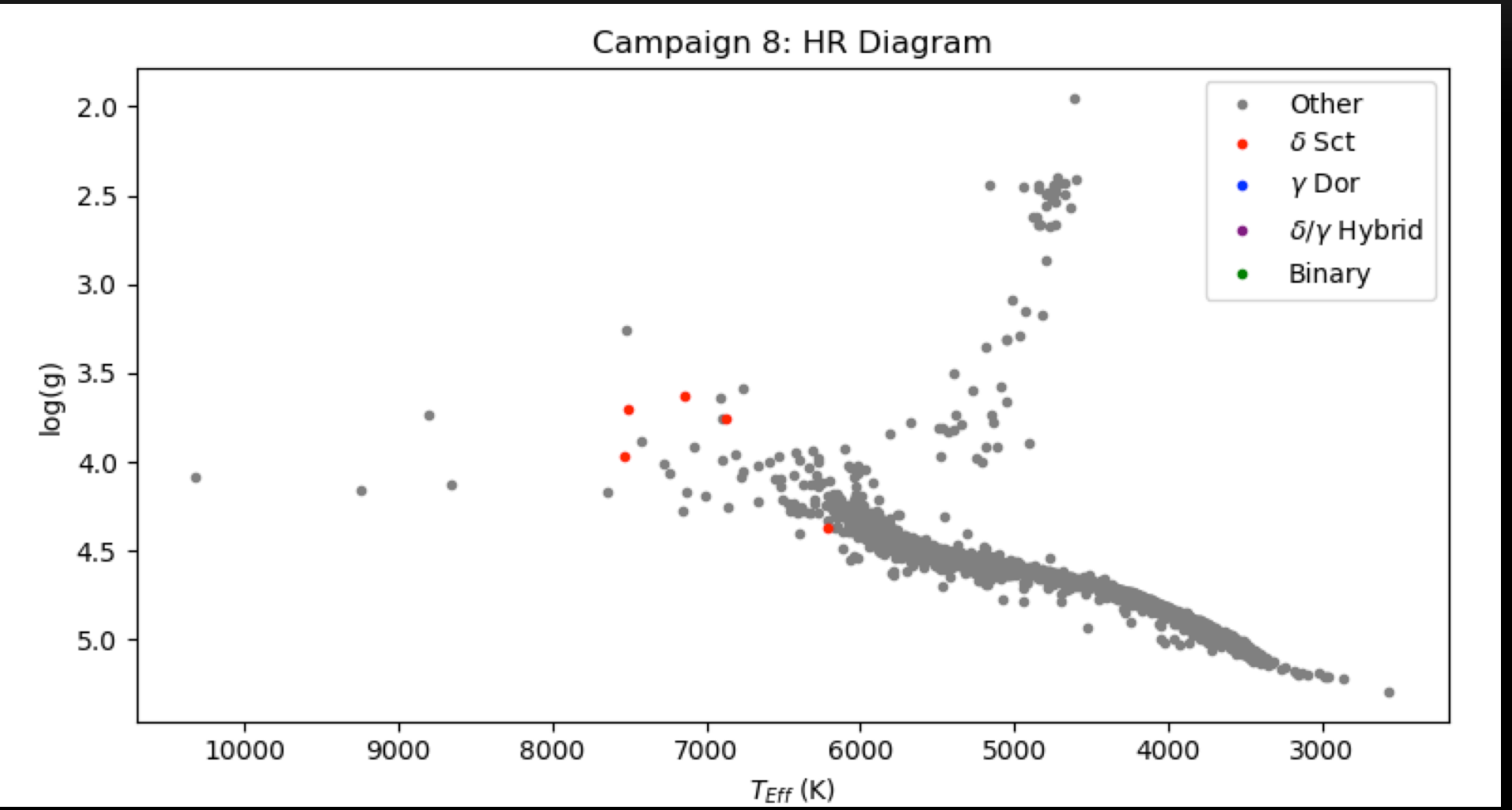
- Pulsate in many simultaneous radial and nonradial acoustic modes (like Sun), and sometimes also in gravity modes (hybrid delta Sct/gamma Dor stars)
- Arguably the most promising type of variable, after Sun/sunlike stars, for using pulsations to infer interior structure
- Similarities to and differences from Sun can be used to test physics input and methods of solar and stellar modeling
- Many interesting phenomena and unanswered questions (e.g., frequency content, amplitudes, peculiar element abundances, unexplained hybrids, . . .)

Analysis of light curves from our K2 Guest Investigator survey revealed about 250 delta Sct candidates

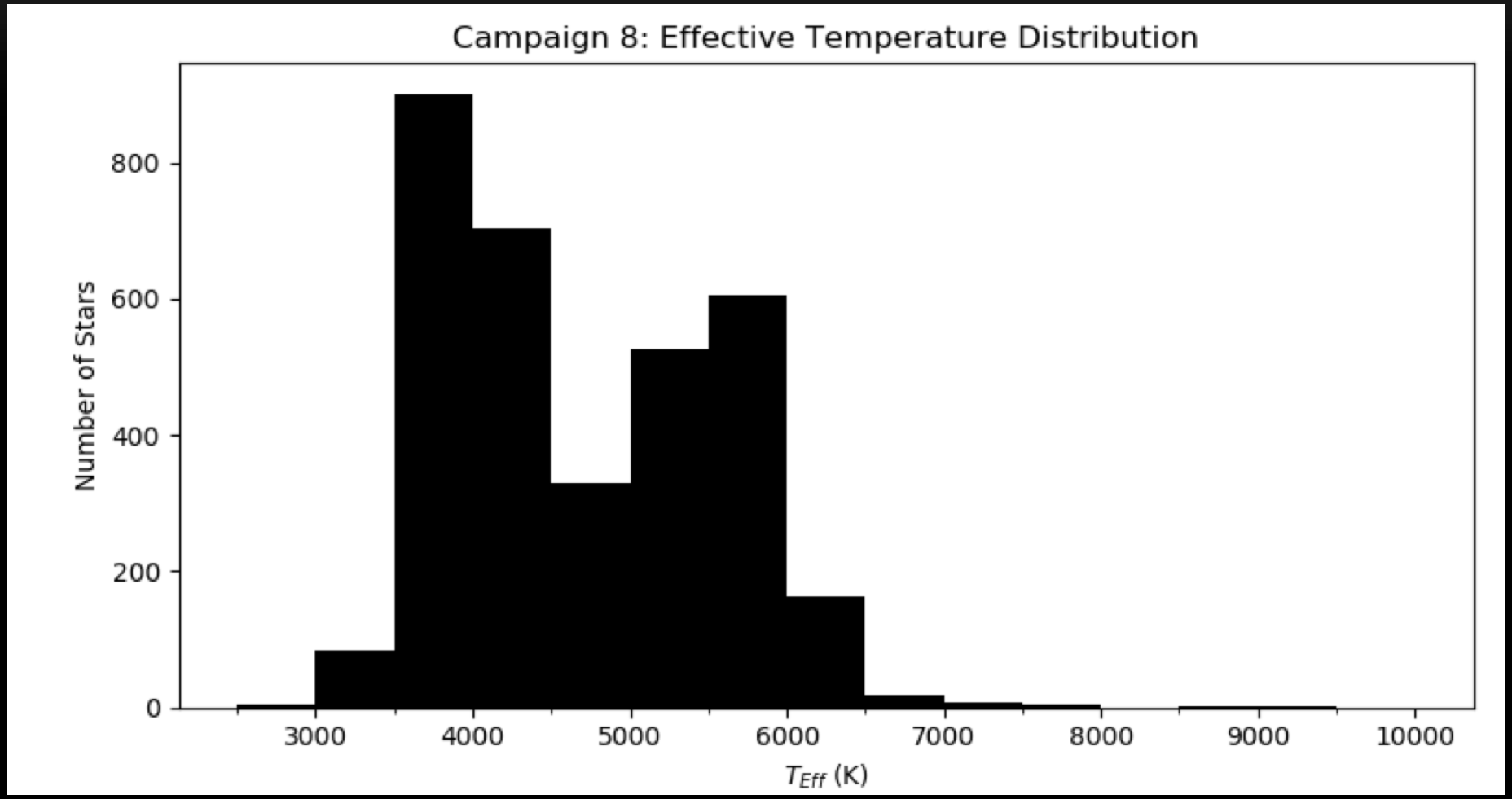
Campaign	# in sample	# δ Sct	Kp_min (bright)	Kp_max (faint)	Comments
C4	894	9	2.99	16.6	Pleiades/Hyades
C5	1268	12	6.20	19.8	M67/Beehive
C6	996	4	6.04	15.0	North Galactic Cap
C7	506	26	7.37	16.5	R147, near Gal. Center
C8	3370	5	6.04	16.0	
C10	2500	5	6.06	15.8	CCD Module 4 lost; North Galactic Cap
C11	2814	108	6.09	13.2	Galactic Center
C12	1859	15	5.98	15.9	
C13	2890	73	5.12	15.9	Hyades
C17	560	2	6.04	15.0	Overlap with C6

Percentage of delta Sct candidates varied from 4% (C11) or 5% (C7) down to only 0.15% (C8)

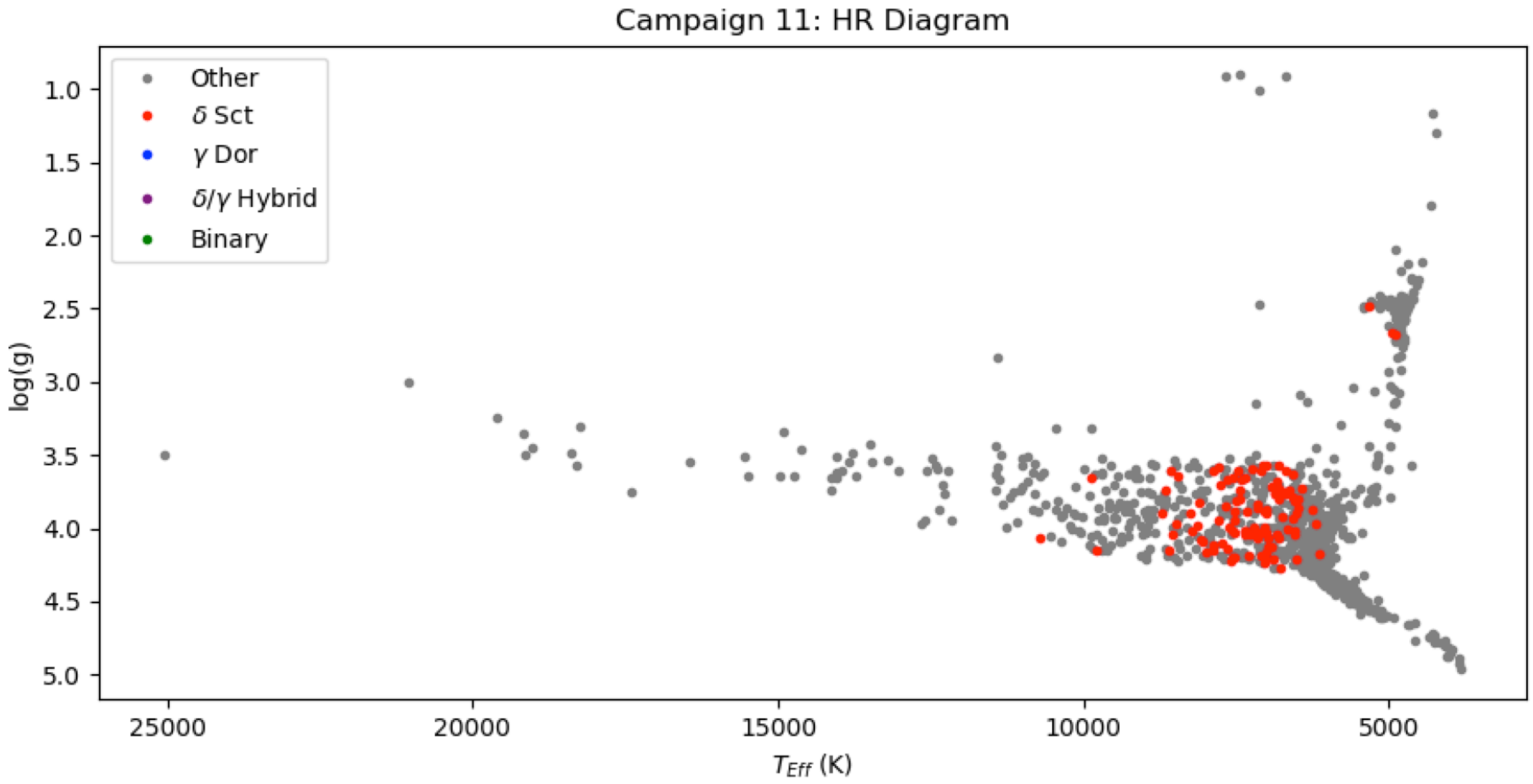
Campaign 8 targets with fewest delta Sct candidates (red dots) included mostly lower main-sequence stars



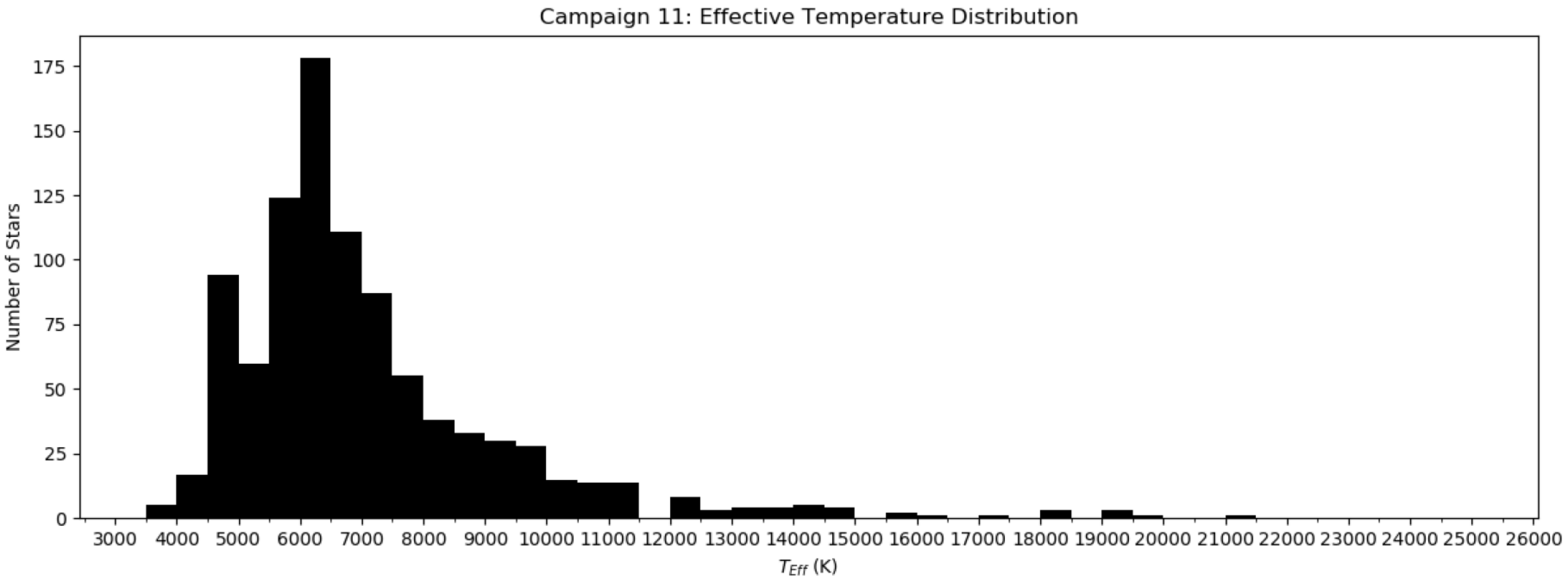
Effective temperatures of most Campaign 8 targets are < 6000 K, cooler than expected for delta Sct stars



Campaign 11 targets with most delta Sct candidates (red dots) contained mostly upper main-sequence stars



Effective temperatures of most Campaign 11 stars are 6000-8000 K, as expected for delta Sct stars



Light curve and amplitude spectrum of delta Sct candidate with largest number of frequencies (34)

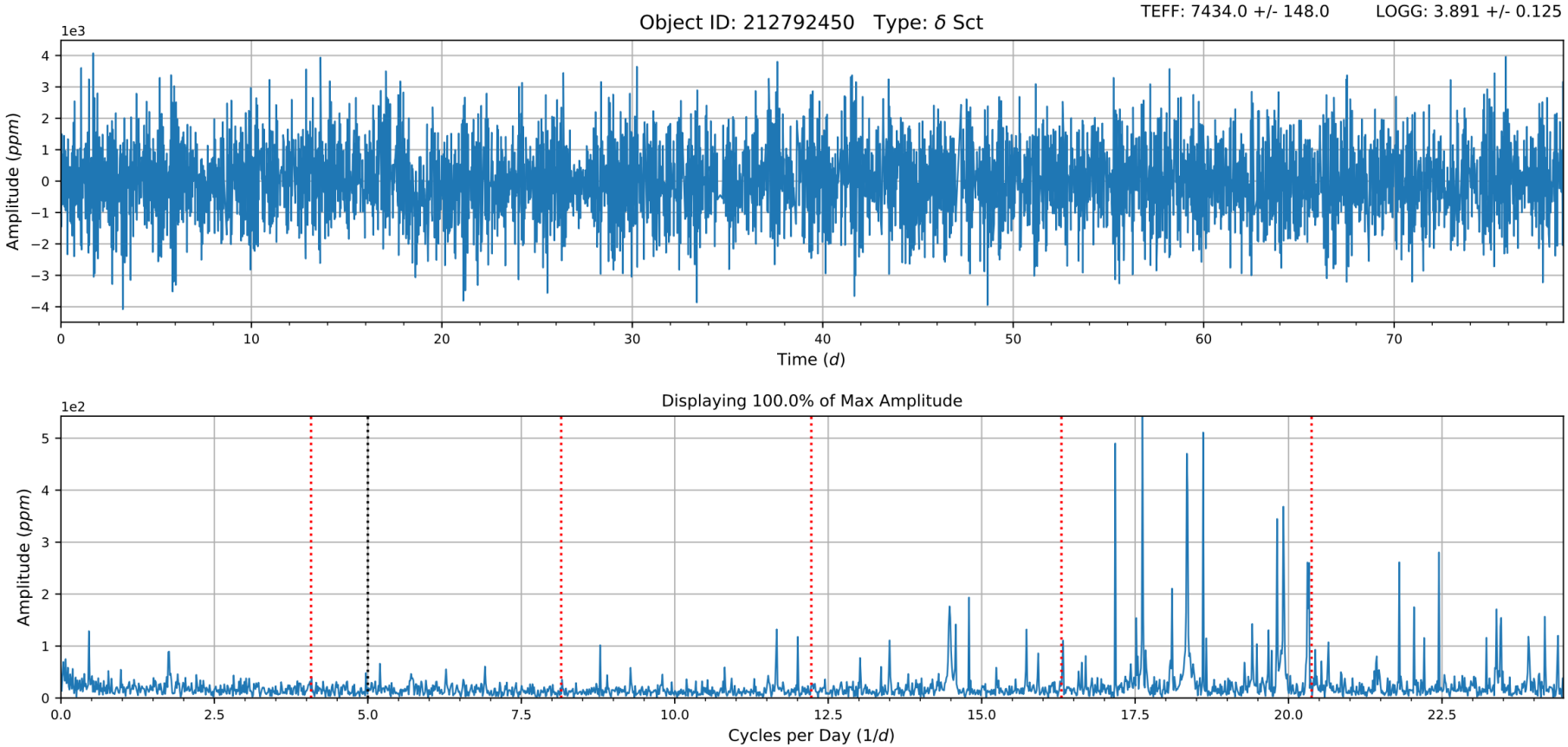
EPIC: 212792450 CAMPAIGN: 6 MODULE: 20 CHANNEL: 69

RA: 203.001 DEC: -5.766 CADENCE: long cadence KP: 9.596

JMAG: 9.012 +/- 0.021 HMAG: 8.907 +/- 0.023 KMAG: 8.855 +/- 0.024 FEH: 0.041 +/- 0.1 RAD: 2.497 +/- 0.491

MASS: 1.879 +/- 0.203 RHO: 0.108 +/- 0.065 LUM: nan +/- nan D: 363.3 +/- 72.48 EBV: 0.055 +/- 0.026

TEFF: 7434.0 +/- 148.0 LOGG: 3.891 +/- 0.125



Light curve and amplitude spectrum of brightest delta Sct candidate (Kp magnitude 5.587)

EPIC: 210425611
RA: 64.99
JMAG: nan +/- nan
MASS: 1.862 +/- 0.14

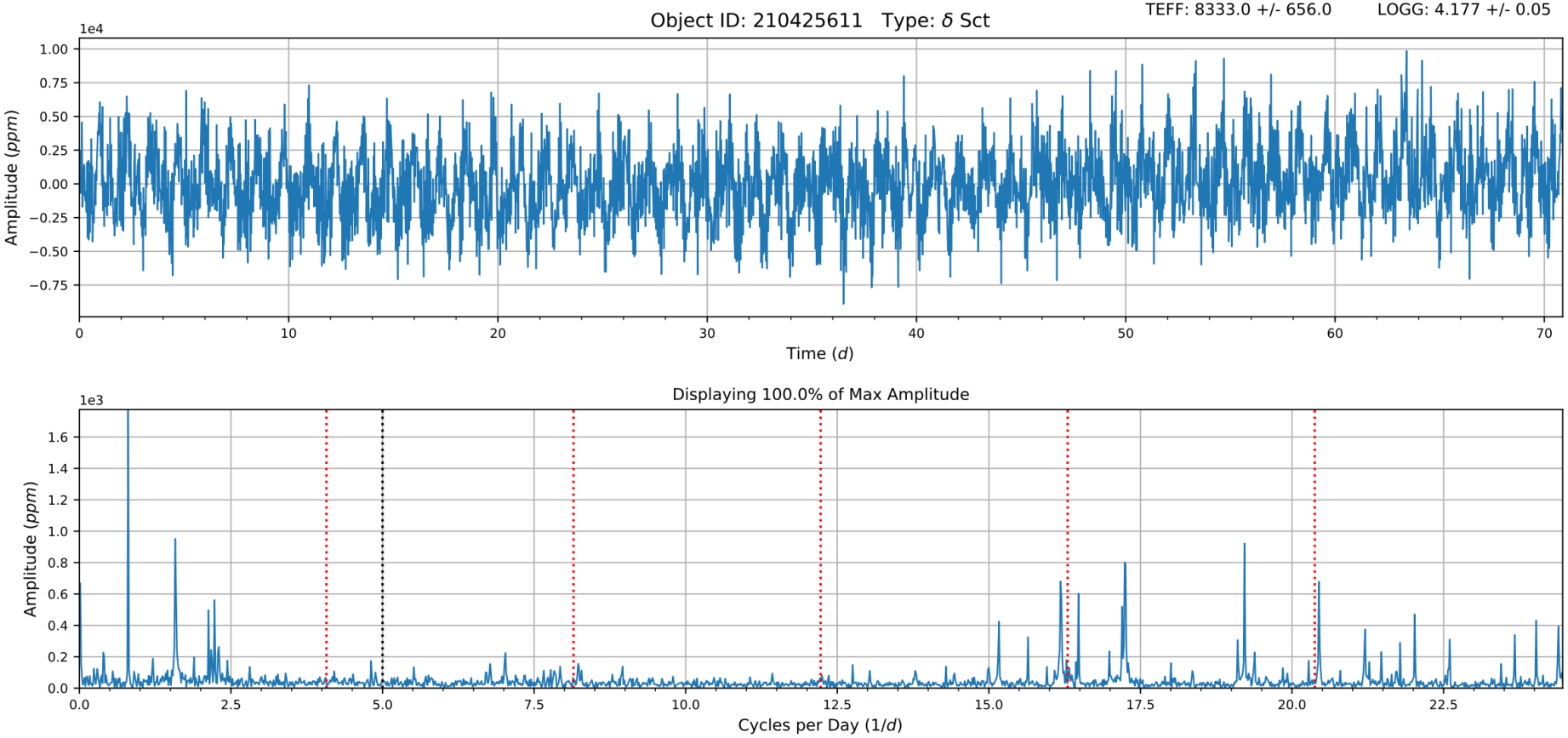
CAMPAIGN: 4
DEC: 14.035
HMAG: nan +/- nan
RHO: 0.294 +/- 0.051

MODULE: 6
CADENCE: long cadence
KMAG: nan +/- nan
LUM: nan +/- nan

CHANNEL: 15
KP: 5.587
FEH: -0.051 +/- 0.12
D: 45.7 +/- 1.371

RAD: 1.846 +/- 0.091
EBV: 0.0 +/- 0.0

TEFF: 8333.0 +/- 656.0
LOGG: 4.177 +/- 0.05



Note also low frequencies!

Light curve and amplitude spectrum of faintest delta Sct candidate (Kp magnitude 15.89)

EPIC: 247333962
RA: 80.083
JMAG: 14.365 +/- 0.026
MASS: 1.14 +/- 0.194

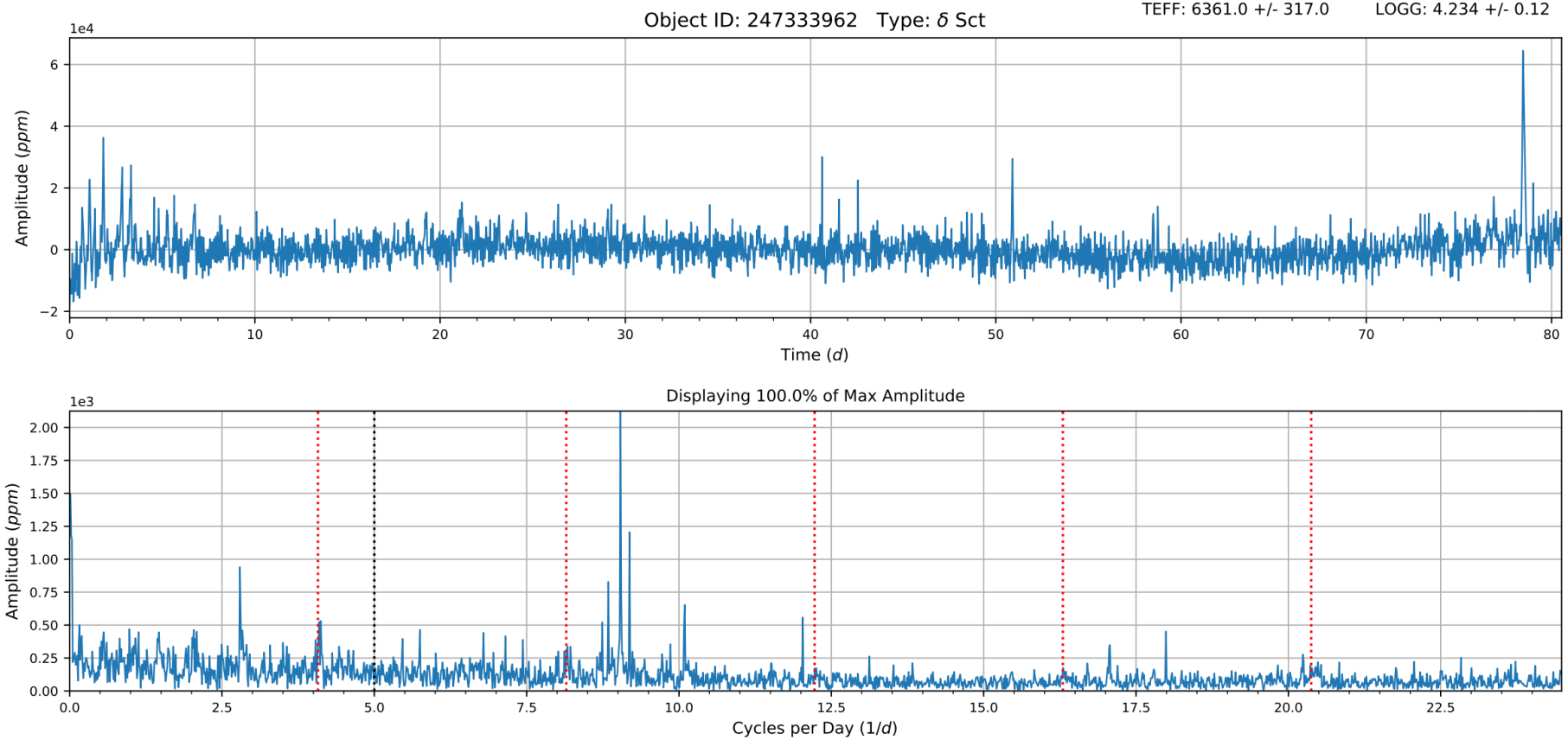
CAMPAIGN: 13
DEC: 20.849
HMAG: 14.072 +/- 0.036
RHO: 0.445 +/- 0.26

MODULE: 2
CADENCE: long cadence
KMAG: 13.98 +/- 0.046
LUM: nan +/- nan

CHANNEL: 3
KP: 15.89
FEH: -0.252 +/- 0.16
D: 1846.0 +/- 527.9

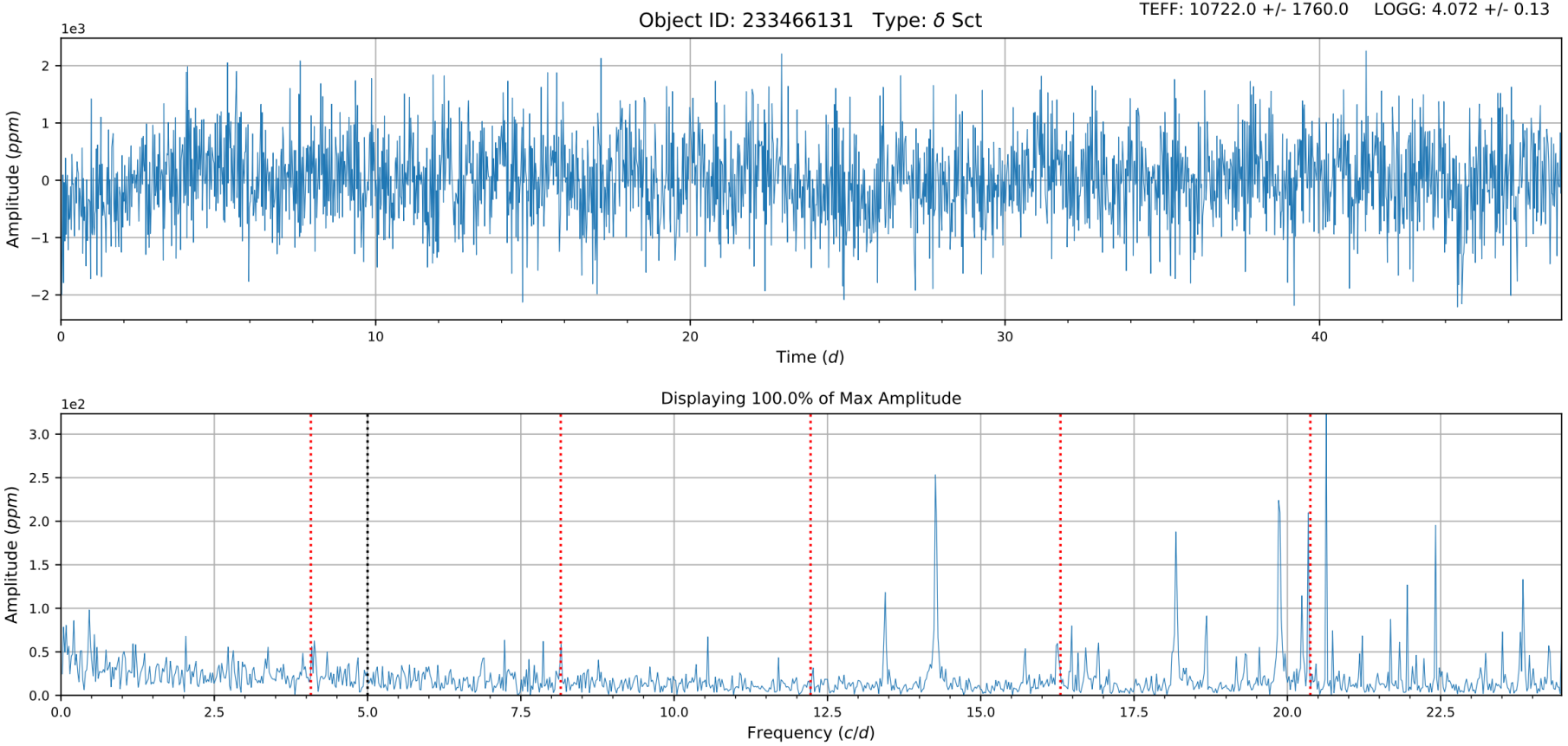
RAD: 1.343 +/- 0.395
EBV: 0.473 +/- 0.175

TEFF: 6361.0 +/- 317.0
LOGG: 4.234 +/- 0.12



Light curve and amplitude spectrum of hottest star (10,722 K) showing p-mode frequencies

EPIC: 233466131 CAMPAIGN: 11 MODULE: 10 CHANNEL: 31
RA: 261.632 DEC: -17.587 CADENCE: long cadence KP: 10.092
JMAG: 8.992 +/- 0.029 HMAG: 9.003 +/- 0.036 KMAG: 9.037 +/- 0.033 FEH: 0.016 +/- 0.12 RAD: 2.529 +/- 0.407
MASS: 2.742 +/- 0.617 RHO: 0.161 +/- 0.088 LUM: nan +/- nan D: 460.0 +/- 67.79 EBV: 0.213 +/- 0.111
TEFF: 10722.0 +/- 1760.0 LOGG: 4.072 +/- 0.13



Light curve and amplitude spectrum of coolest star (4950 K) showing p-mode frequencies

EPIC: 235864398
RA: 258.397
JMAG: 8.31 +/- 0.024
MASS: 2.415 +/- 0.413

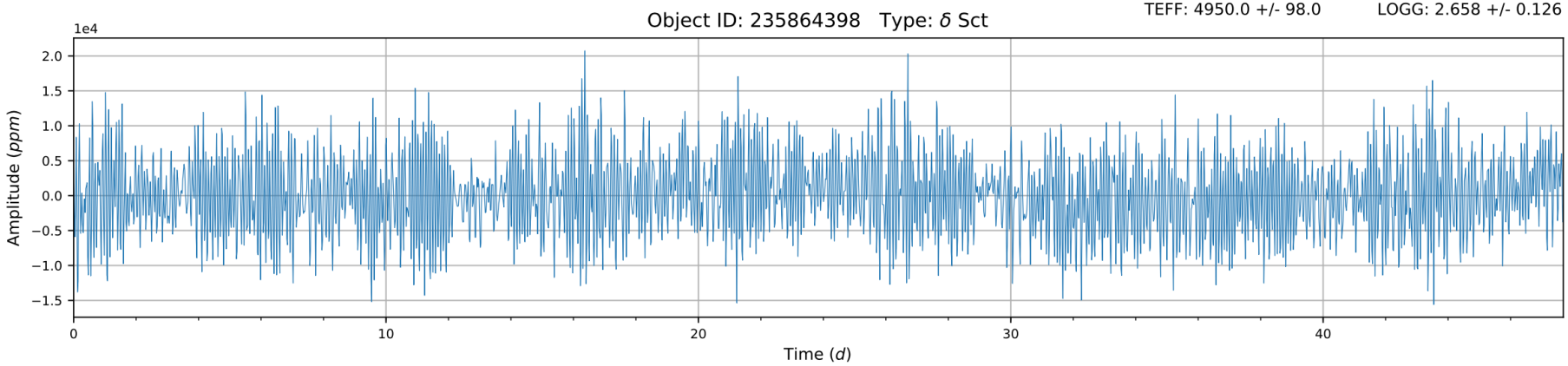
CAMPAIGN: 11
DEC: -29.122
HMAG: 7.824 +/- 0.018
RHO: 0.001 +/- 0.001

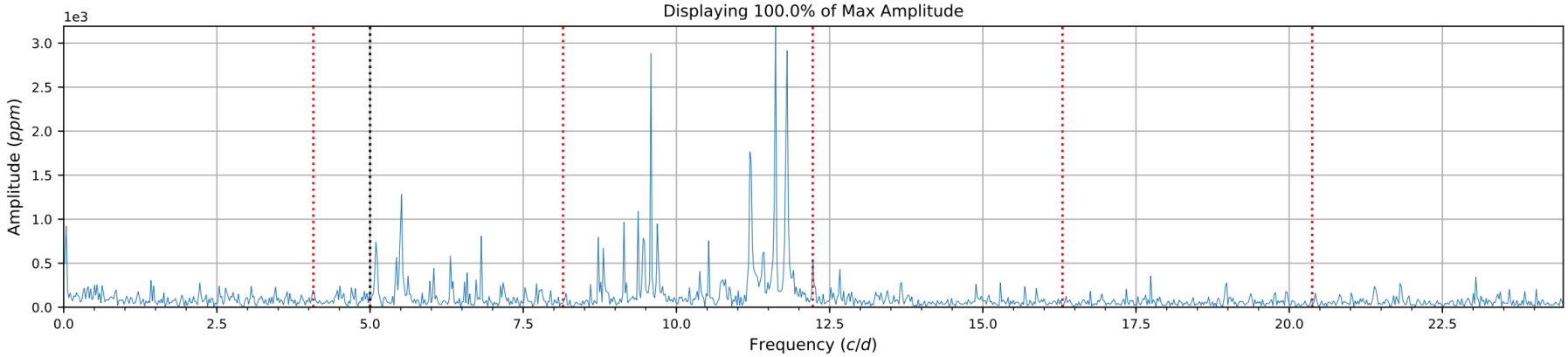
MODULE: 16
CADENCE: long cadence
KMAG: 7.736 +/- 0.023
LUM: nan +/- nan

CHANNEL: 54
KP: 10.073
FEH: -0.05 +/- 0.15
D: 835.7 +/- 148.8

RAD: 11.132 +/- 2.993
EBV: 0.238 +/- 0.088

TEFF: 4950.0 +/- 98.0
LOGG: 2.658 +/- 0.126





Light curve and amplitude spectrum of delta Sct candidate with highest amplitude modes (60 parts per thousand)

EPIC: 240323947
RA: 264.391
JMAG: 10.008 +/- 0.032
MASS: 2.192 +/- 0.947

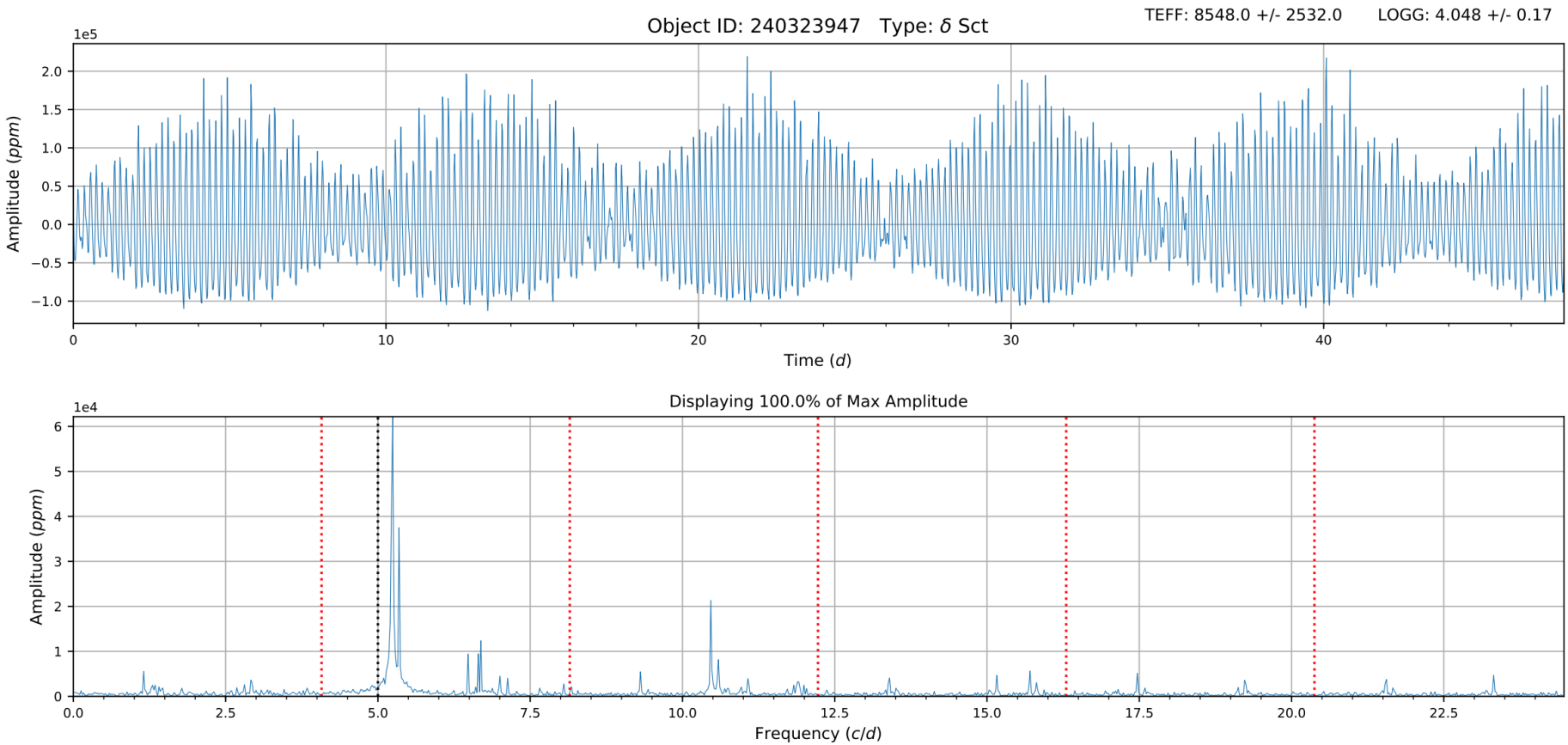
CAMPAIGN: 11
DEC: -29.757
HMAG: 9.767 +/- 0.048
RHO: 0.156 +/- 0.148

MODULE: 6
CADENCE: long cadence
KMAG: nan +/- nan
LUM: nan +/- nan

CHANNEL: 16
KP: 11.506
FEH: 0.052 +/- 0.15
D: 866.1 +/- 648.4

RAD: 2.399 +/- 1.114
EBV: 0.359 +/- 0.218

TEFF: 8548.0 +/- 2532.0
LOGG: 4.048 +/- 0.17



Light curve and amplitude spectrum of delta Sct candidate showing eclipses in light curve

EPIC: 247553546
RA: 74.488
JMAG: 13.975 +/- 0.026
MASS: 1.513 +/- 0.218

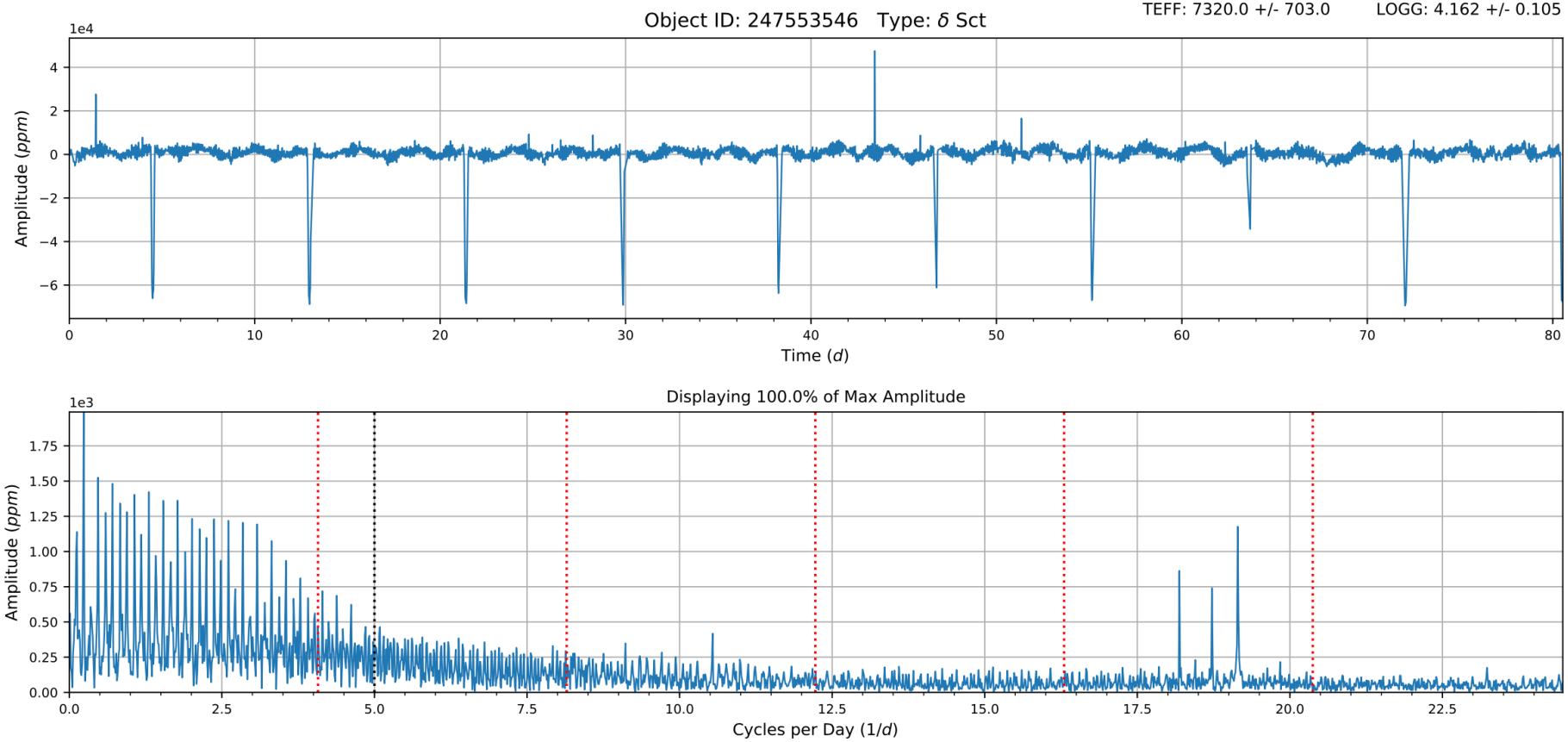
CAMPAIGN: 13
DEC: 22.606
HMAG: 13.804 +/- 0.034
RHO: 0.313 +/- 0.155

MODULE: 8
CADENCE: long cadence
KMAG: 13.741 +/- 0.056
LUM: nan +/- nan

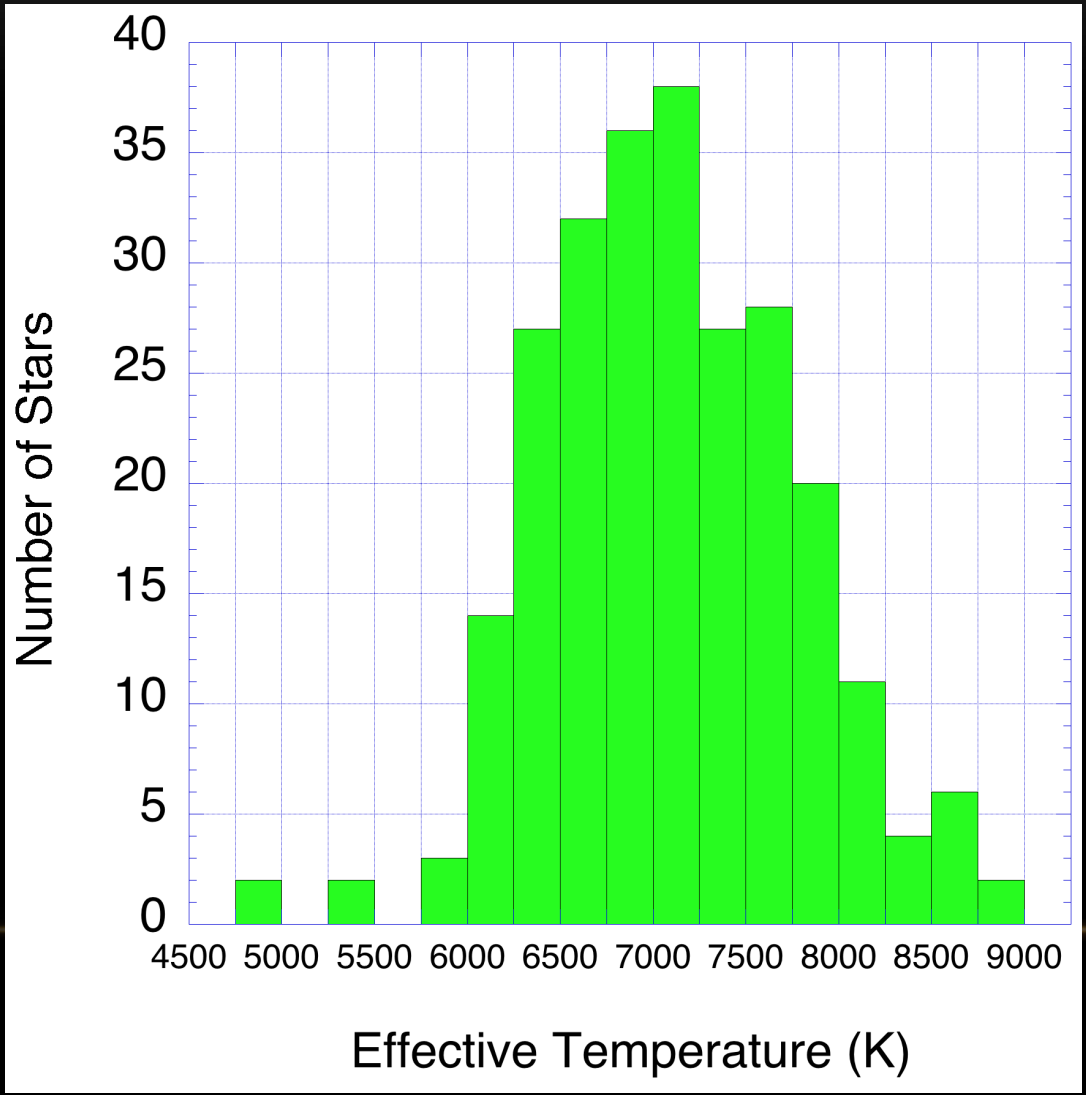
CHANNEL: 22
KP: 15.193
FEH: -0.173 +/- 0.09
D: 2110.0 +/- 493.0

RAD: 1.65 +/- 0.347
EBV: 0.495 +/- 0.197

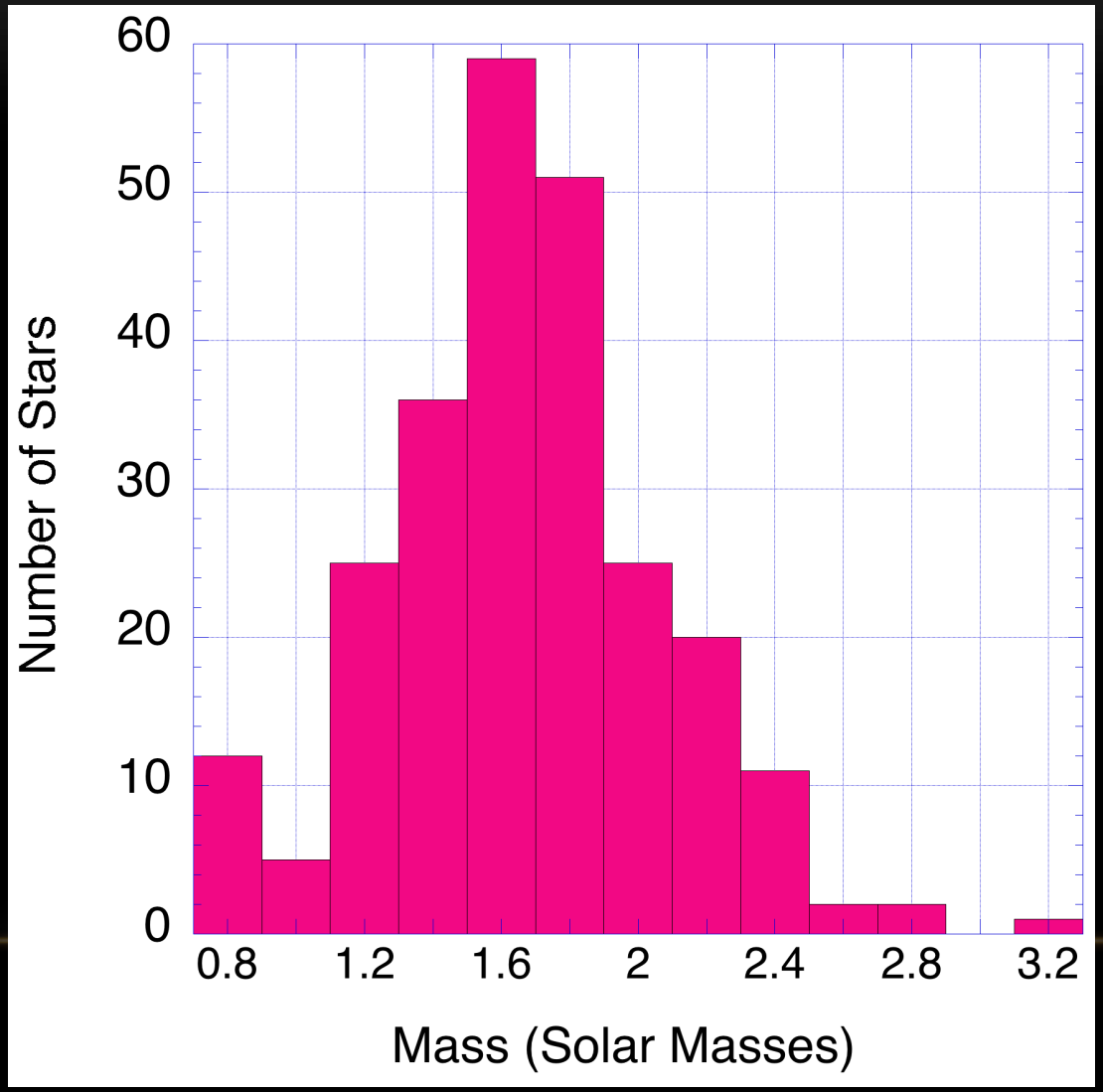
TEFF: 7320.0 +/- 703.0
LOGG: 4.162 +/- 0.105



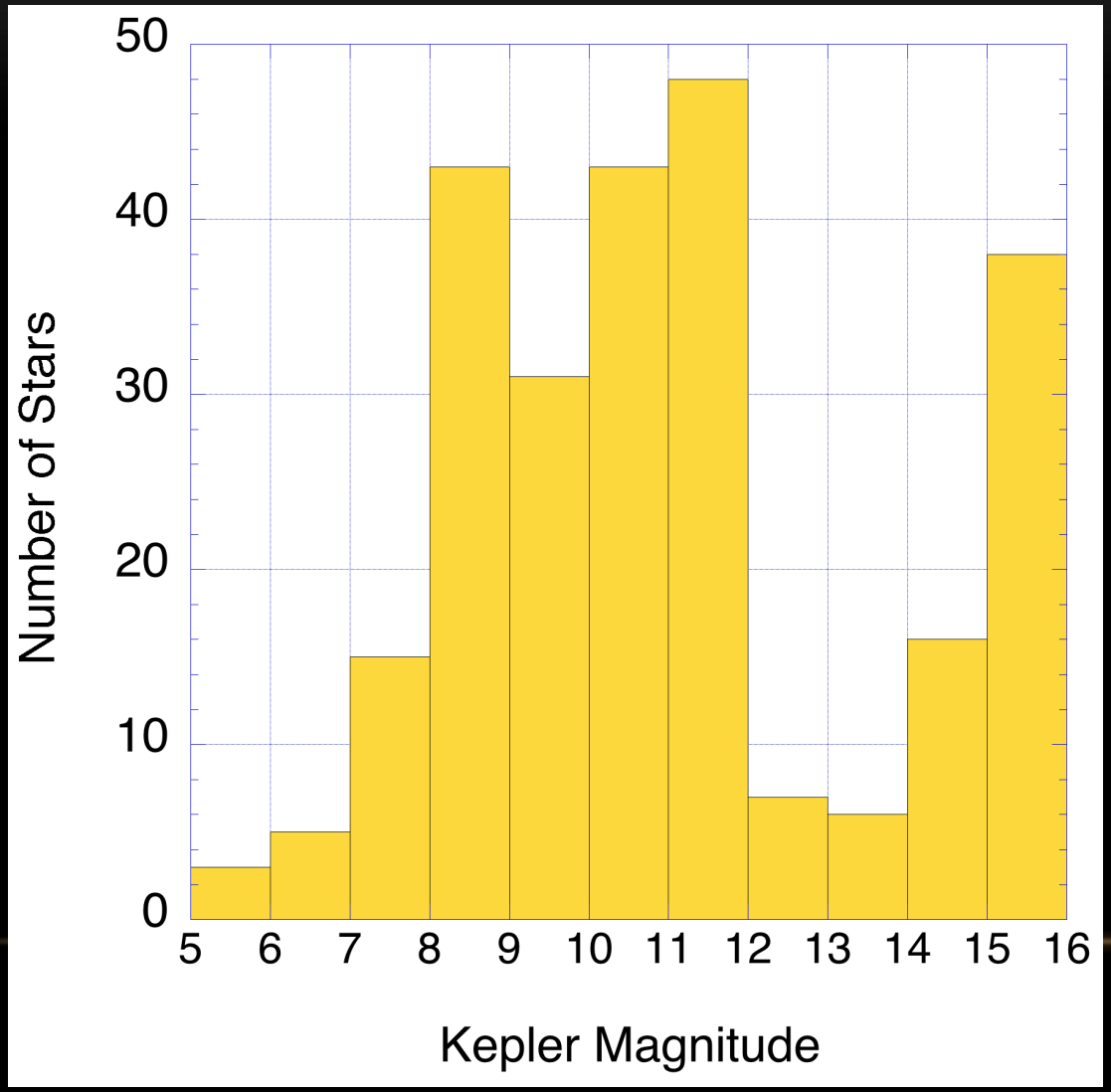
The effective temperatures of delta Sct candidates are about 7000 K as expected, but a few stars are cooler, and some of the hottest stars may be beta Cep variables



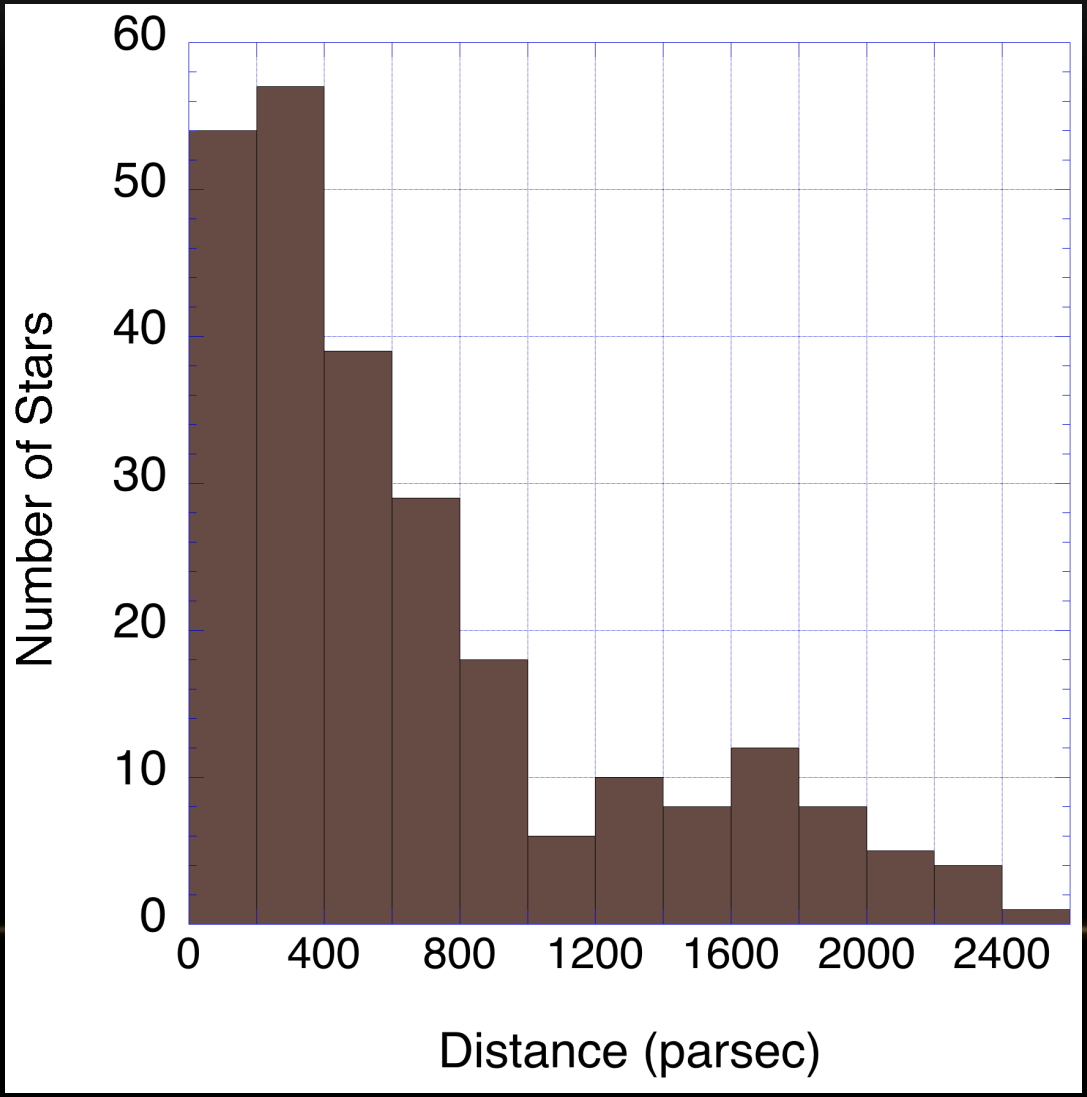
The mass distribution (as estimated in the K2 EPIC catalog) peaks at 1.6-2 solar masses, as expected for delta Sct stars



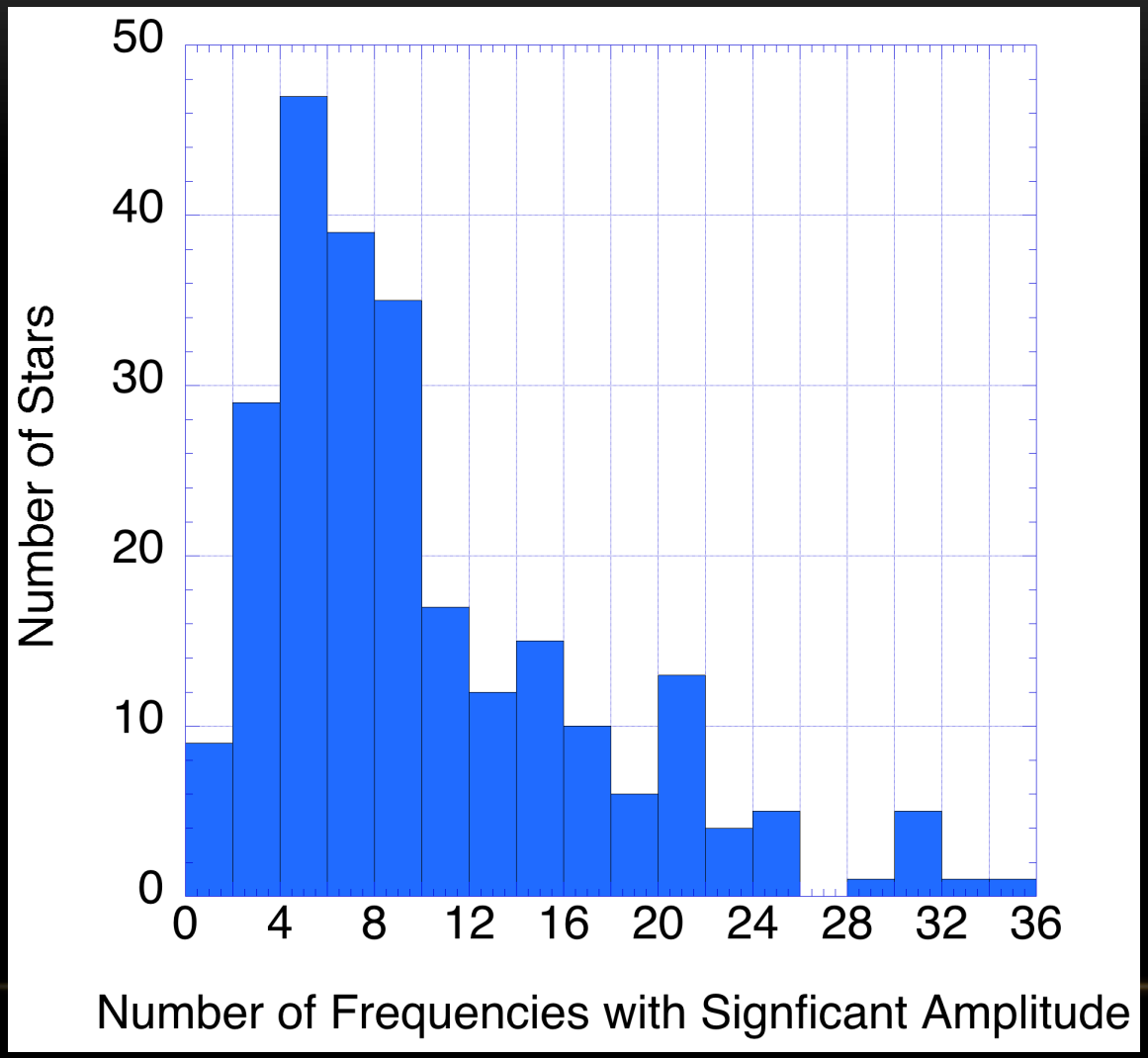
Kp magnitudes of many delta Sct candidates are 8-12, but pulsations are easily visible in the amplitude spectrum of even the fainter 14-16 mag candidates



Most of the delta Sct candidates are nearby, but some stars at a distance around 1600 parsecs may be part of a more distant young cluster or Milky Way spiral arm



Most delta Sct candidates show 4 to 10 p-mode pulsations (frequency > 5 cycles/day) with signal-to-noise ratio > 4



Conclusions

- *Kepler* has obtained unprecedented long time-series high signal-to-noise photometric data enabling the discovery and characterization of variable stars pulsating in many simultaneous radial and nonradial modes

- We have identified 249 obvious delta Sct candidates so far in our K2 Guest Observer data for eleven (out of 19) K2 campaigns. Some of these stars were known as delta Sct stars before *Kepler*

- A few of these candidates have anomalously low T_{eff} for a delta Sct star, and a few have a very high T_{eff} and may be beta Cep stars

- 126 out of 249 candidates show low frequencies < 5 c/d that may be gamma Dor g-mode pulsations

Many remaining physics questions

- Why are all expected frequencies not observed?
- Why are there no correlations between stellar properties and pulsation properties (e.g., pulsation amplitudes, frequency content)?
- Why do some stars in instability regions not show any pulsations?
- Why are there so many hybrid gamma Dor/delta Sct stars, in contradiction to theoretical expectations?
- What determines the amplitudes of individual modes?
- Do amplitudes or frequency content vary with time?

Some Future Work

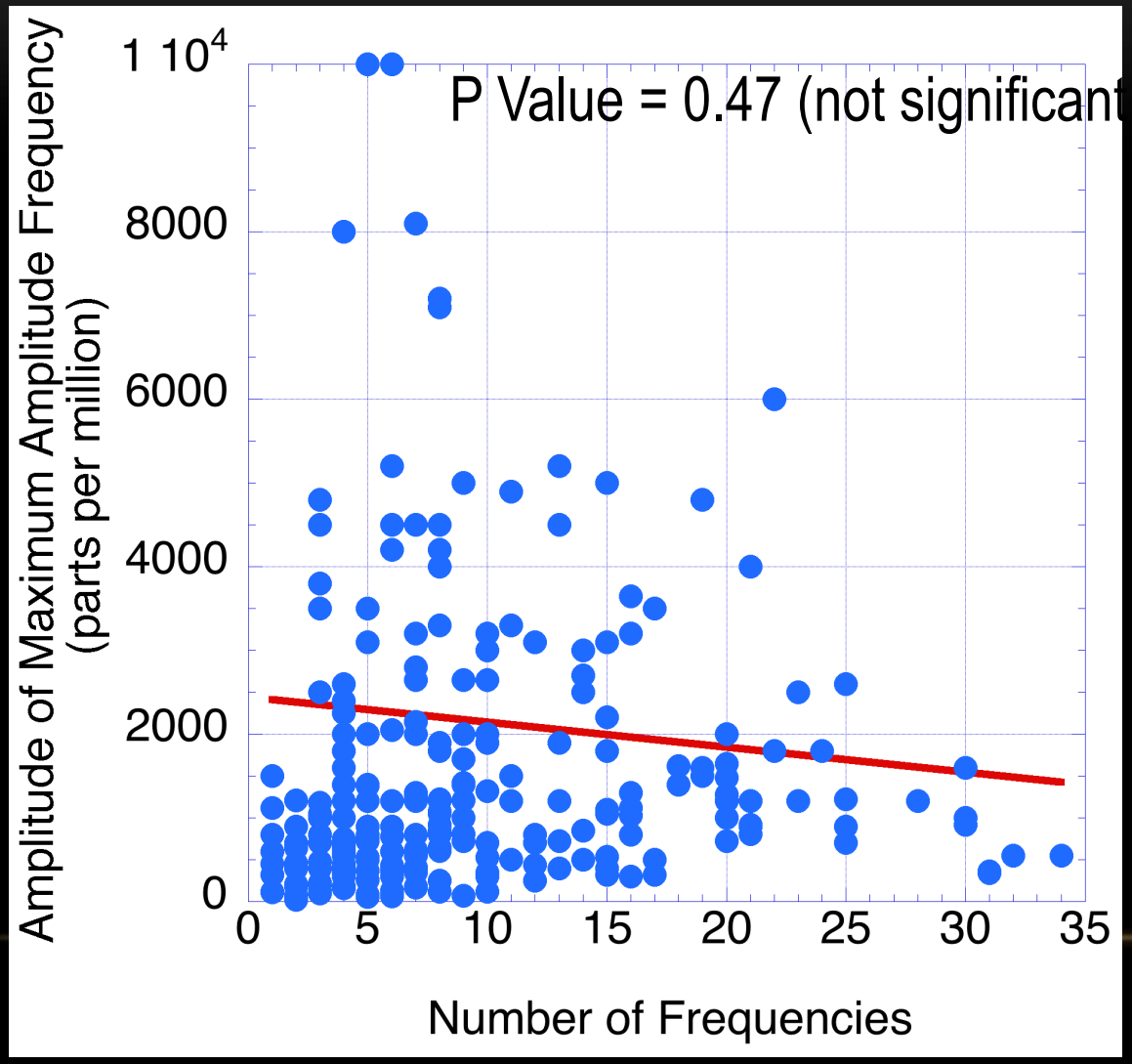
- Asteroseismic modeling to address many unsolved problems for A-F type main-sequence stars

- Literature search for individual stars -- How many are newly discovered delta Sct stars? If known as delta Sct stars before, have amplitudes or frequency content changed? How may pulsation frequencies could be identified before *Kepler* compared to those found using *K2* data?

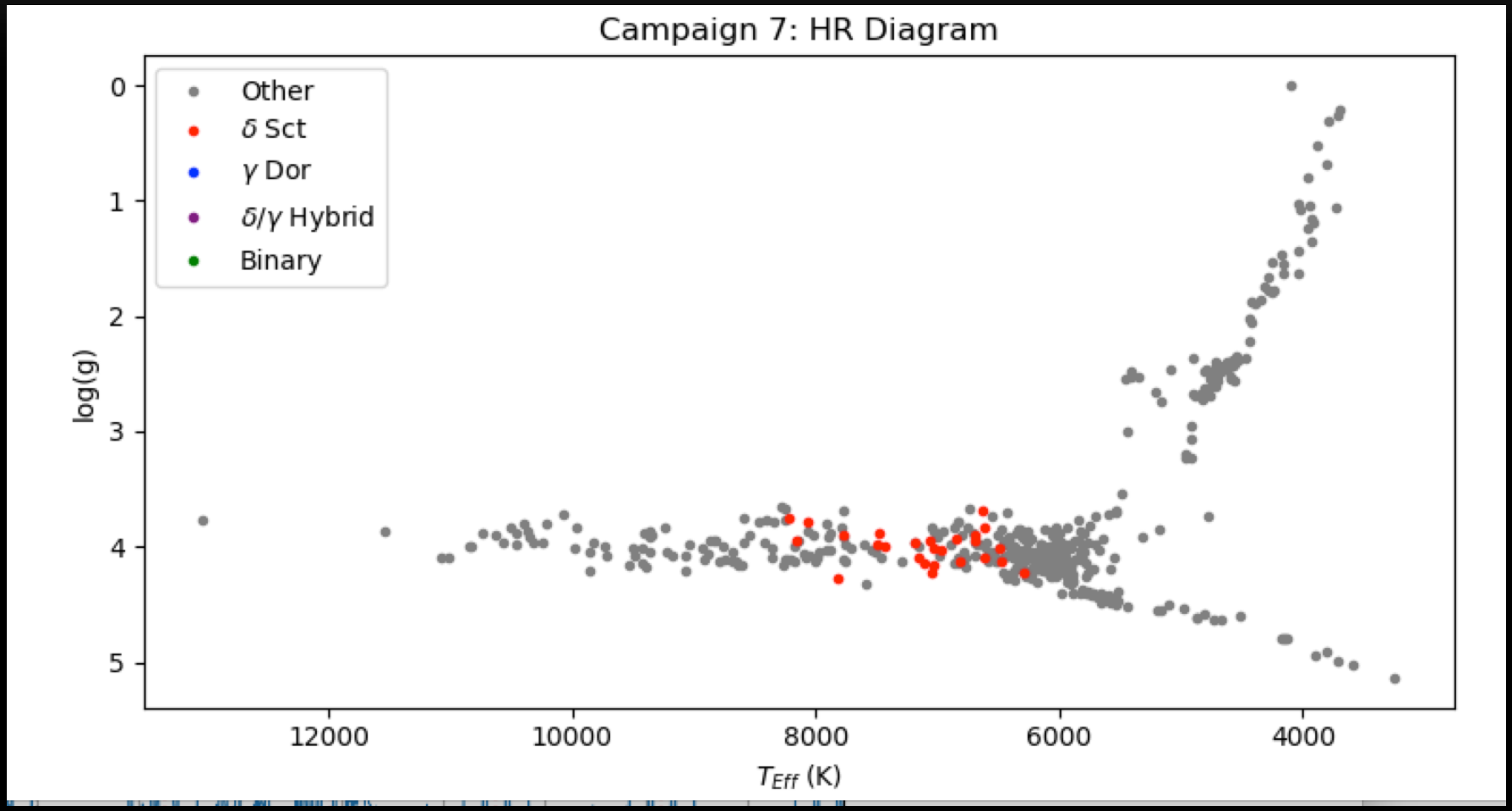
- Ground-based follow-up observations for more accurate constraints for asteroseismic modeling

- How would new observations, e.g., photometric or spectroscopic ground-based monitoring, or observations by the TESS spacecraft, be useful?

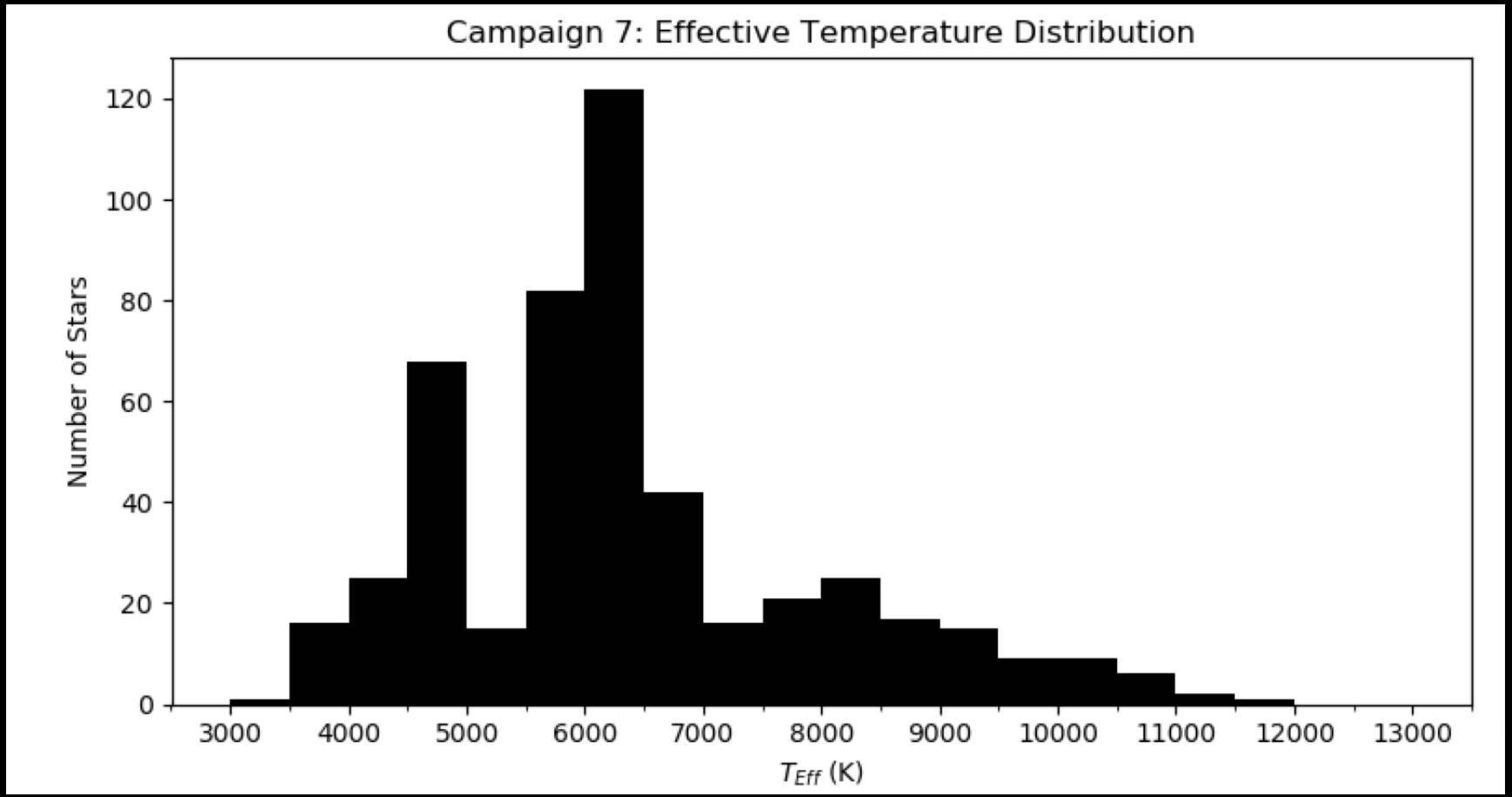
We could not find any significant correlations between stellar properties (e.g., T_{eff}, log) and/or pulsation properties



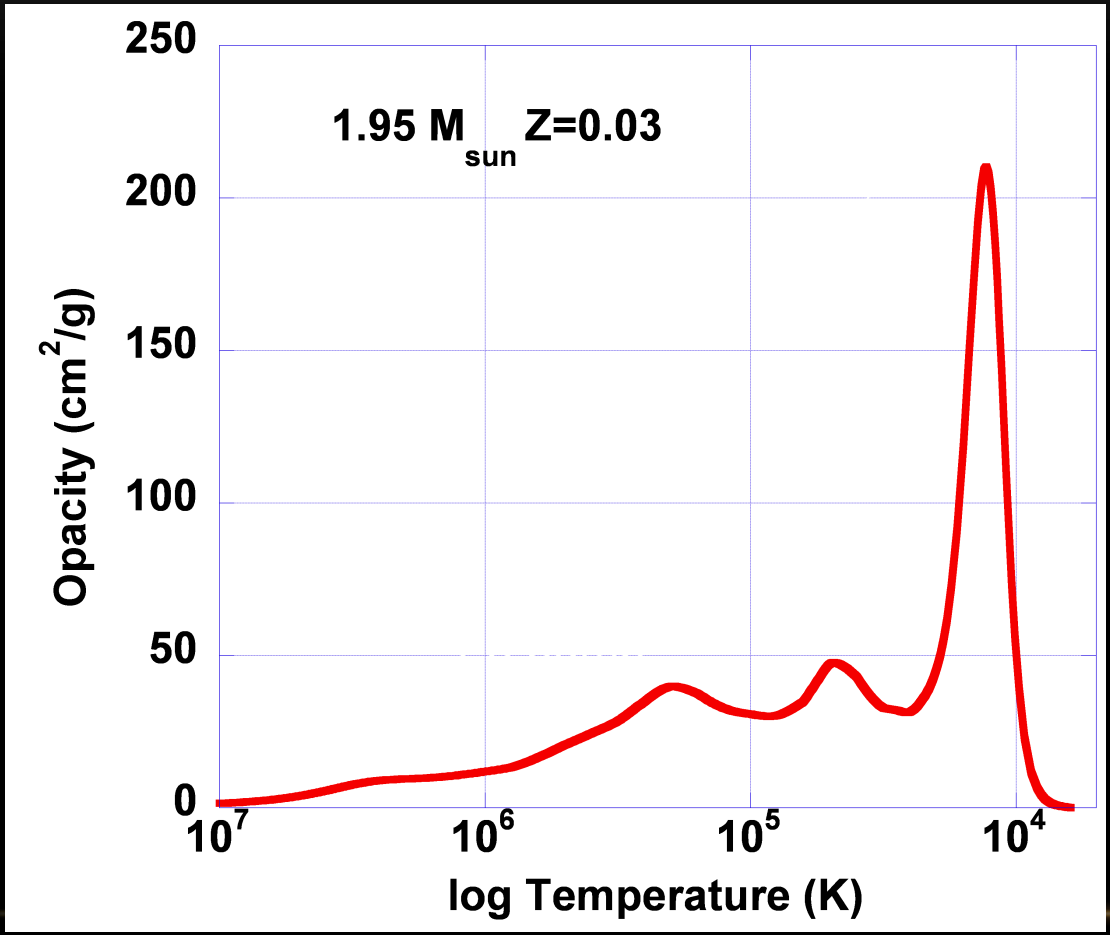
Campaign 7 targets with 26 (5%) delta Sct candidates also included many upper main-sequence stars



Effective temperatures of many Campaign 7 stars are 6000-7000 K, more typical of gamma Dor stars

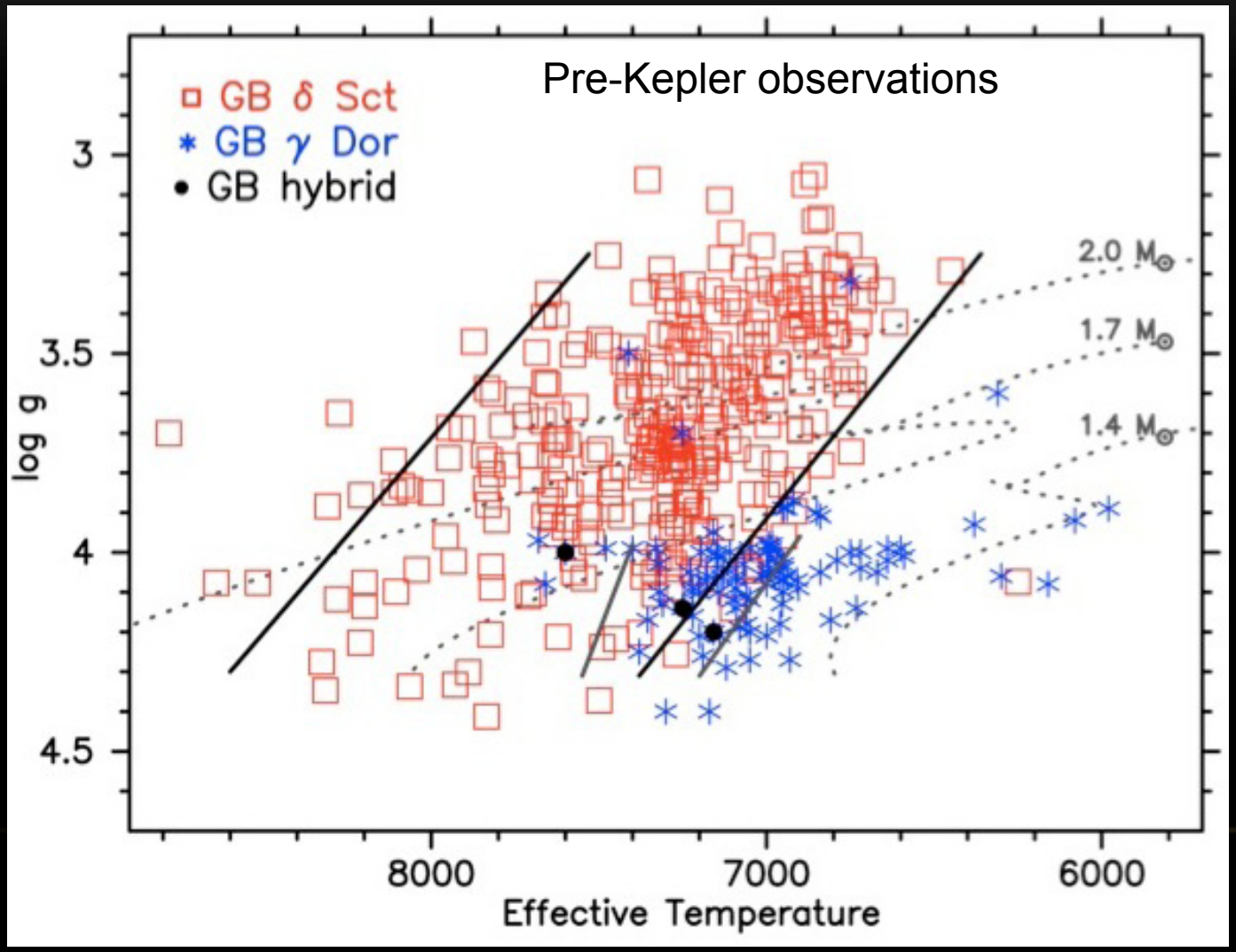


The delta Sct pulsations are driven by the ‘kappa effect’ from second ionization of helium at ~50,000 K

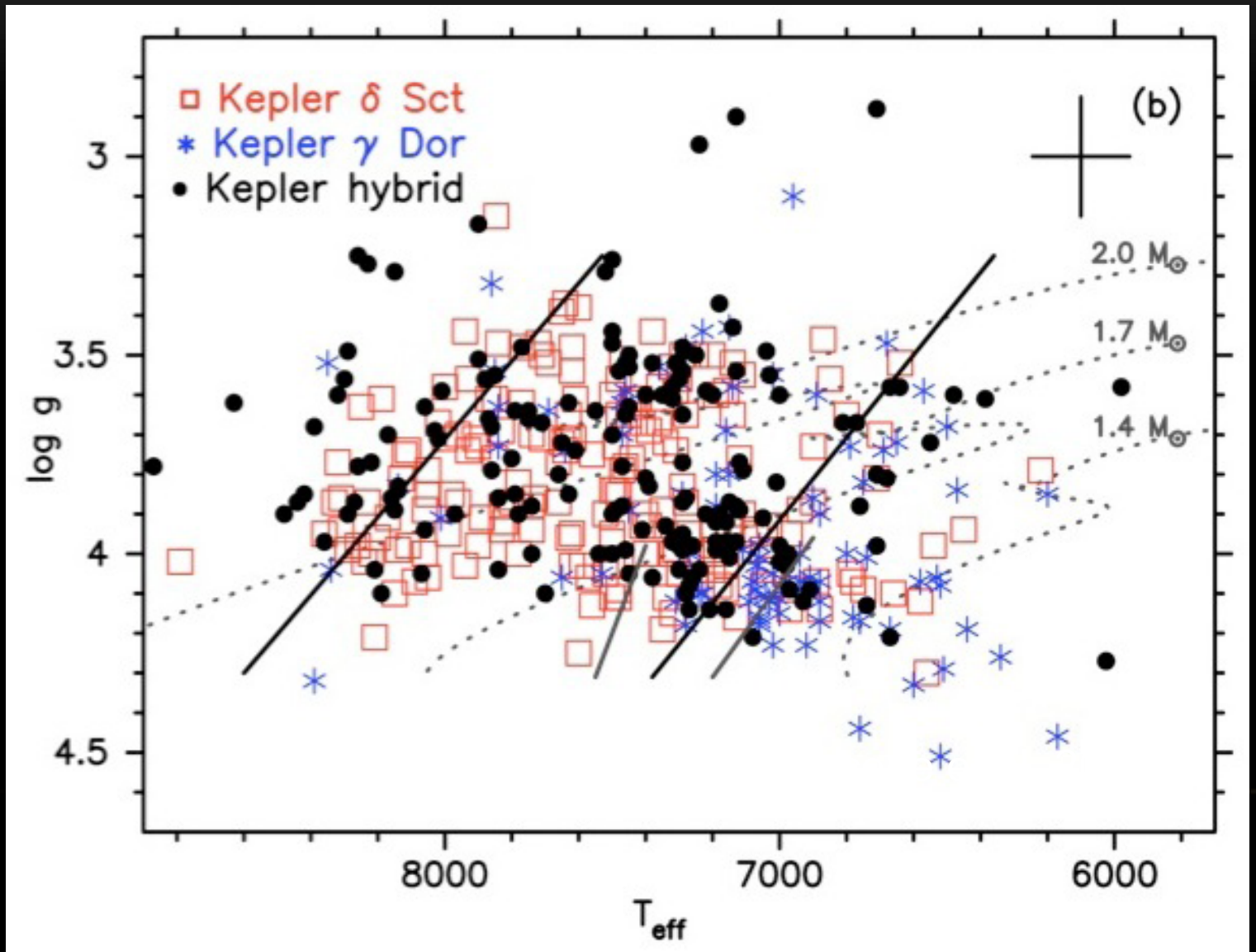


(*kappa* effect: J. P. Cox 1985; Chevalier 1971; Baker and Kippenhahn 1962)

Before *Kepler*, gamma Dor and delta Sct stars mostly fit into instability regions explained by theoretical models, and few hybrids were known



First analysis of *Kepler* data showed many hybrids, and no clean separation of stellar types



Light curve and amplitude spectrum of star with one of highest amplitudes, 1.8e4 ppm or 18 parts per thousand

EPIC: 234201903
RA: 259.718
JMAG: 7.751 +/- 0.026
MASS: 2.379 +/- 0.425

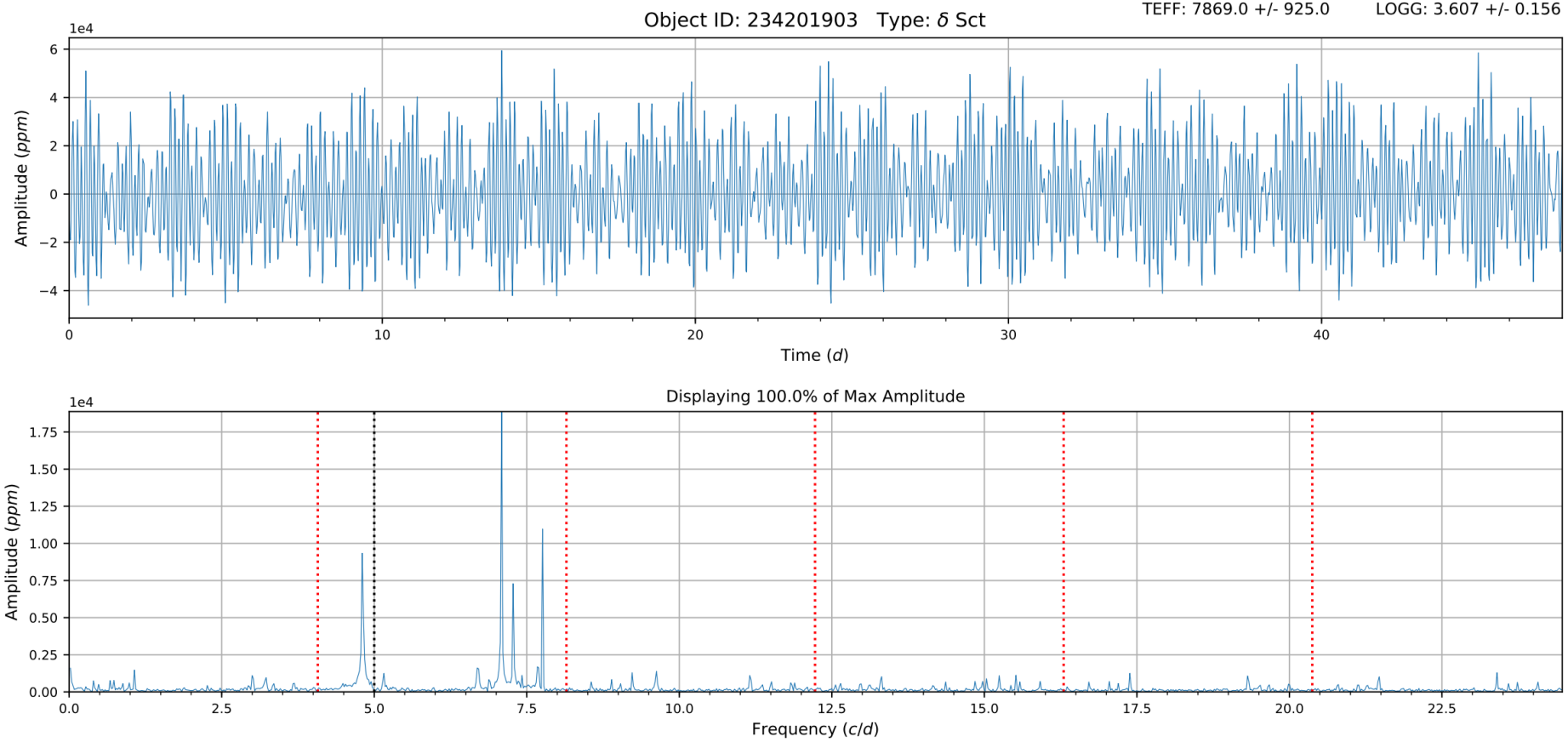
CAMPAIGN: 11
DEC: -20.499
HMAG: 7.644 +/- 0.042
RHO: 0.037 +/- 0.026

MODULE: 14
CADENCE: long cadence
KMAG: 7.555 +/- 0.021
LUM: nan +/- nan

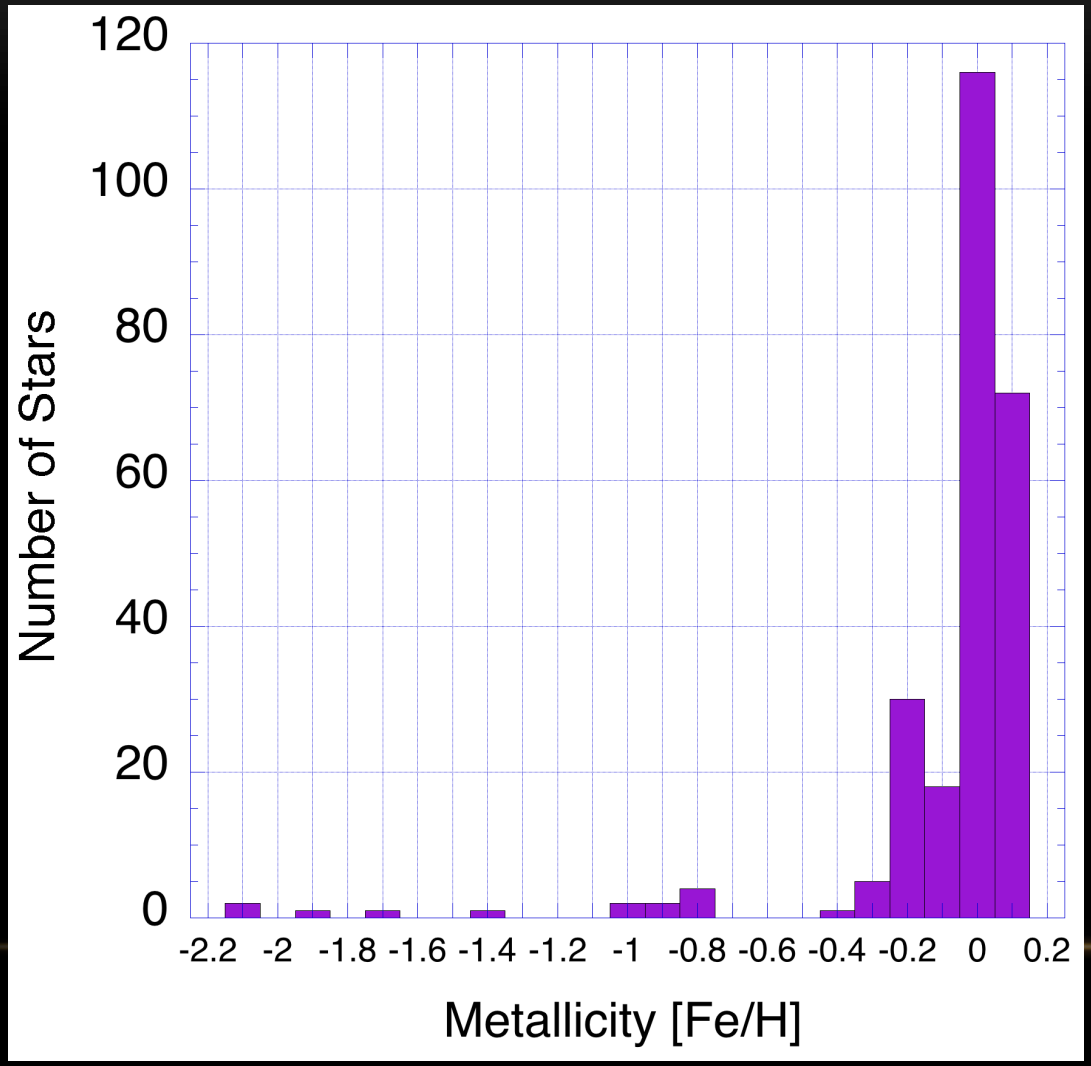
CHANNEL: 47
KP: 8.629
FEH: 0.046 +/- 0.1
D: 341.8 +/- 55.79

RAD: 3.889 +/- 0.622
EBV: 0.197 +/- 0.159

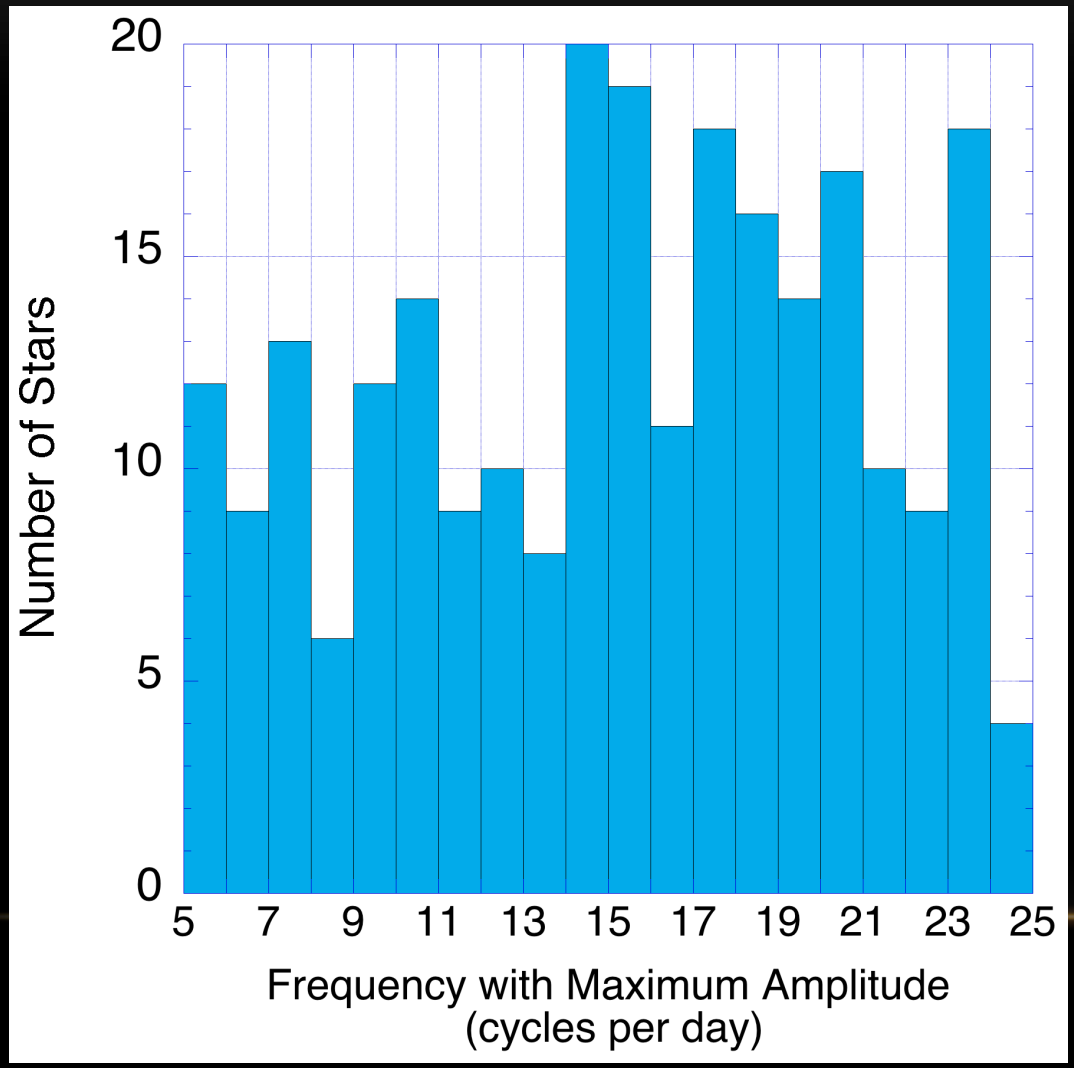
TEFF: 7869.0 +/- 925.0
LOGG: 3.607 +/- 0.156



The metallicities of the delta Sct candidates are near solar, but there are a few stars with metallicities only 1/10 to 1/100 solar



The range of delta Sct frequencies with highest amplitude is distributed between 5 c/d (cutoff criterion for delta Sct stars) and 24.5 c/d (Nyquist limit for 30-minute cadence observations)



Most candidate delta Sct stars show low-amplitude pulsation modes, < 2 parts per thousand