51 Pegasi and Tau Boötis: Planets or Pulsations?

S. D. Horner
Pennsylvania State University
T. M. Brown, E. J. Kennelly, & R. Kotak
High Altitude Observatory
and
S. Jha, S. G. Korzennik, M. Krockenberger, P. Nisenson, & R. W. Noyes
Harvard–Smithsonian Center for Astrophysics

I. Introduction

It recently has been suggested (Gray 1997) that the radial velocity variations observed in the spectra of 51 Pegasi are the result of stellar pulsations as opposed to the reflex motion due to an orbital companion. The AFOE group has confirmed the radial velocity variations of both 51 Pegasi and τ Boötis. Here we discuss the results of a search for evidence of pulsations in the AFOE data for these two stars, as well as attempt to clear up misconceptions regarding pulsations circulated as a result of the current debate about the nature of the 51 Pegasi radial velocity variations.

Star	SpT	Period	Amplitude	$V\sin i$	e
51 Pegasi	G5V	4.23 days	56 m/s	2 km/s	0.01
τ Boötis	F7V	3.31 days	465 m/s	14 km/s	0.00

51 Pegasi – Has a temperature and color very similar to the Sun's. 51 Pegasi may be slightly evolved, and has a slight overabundance of heavy elements.

τ Boötis – Is believed to be young (2 Gyr) and also metal rich.

II. Pulsations

- **p-mode oscillations have periods equal to or shorter than the sound travel time across the star, which for Sun–like stars is on the order of 1 hour.**
- **g-mode oscillations can have longer periods, but g-mode pulsations cannot propagate through convection zones and never have been observed *conclusively* on the Sun.**
- **k, which is related to the ratio of horizontal to vertical amplitude of a pulsation, in the limit of small ω is given approximately by**

  $$k \simeq \frac{N}{\omega},$$

  where N is the buoyancy or Brunt–Väisälä frequency.
- **The periods of radial velocity variations observed in the stars reported to harbor hot Jupiters are greater than 75 hours. For cool main–sequence stars, $N \simeq 0.05$ within a factor of about 2, thus if the variations are the result of pulsations,**

  $$k \simeq \frac{N}{\omega} \geq 10^4.$$

  Therefore, the dynamical motions with periods of several days should consist of flows that are almost entirely *horizontal*.

- **The radiative cooling times for cool stars are only a few seconds, so for long period oscillations, the photosphere behaves non-adiabatically. This results in the temperature and hence brightness variations being much smaller than the corresponding pressure variations. So, for long period oscillations on Sun–like stars, one would not expect to be able to detect photometric variations.**

III. Observations

- The Advanced Fiber Optic Echelle (AFOE) is a fiber–fed, bench–mounted, stabilized, echelle spectrograph located at the 1.5m telescope at Whipple observatory.

- Designed for precise radial velocity measurements, the AFOE is optimized for asteroseismology and extra–solar planet detection.

- The AFOE extra–solar planet detection project has confirmed the radial velocity variations of 51 Pegasi and τ Boötis.

- The resolution of the AFOE is $\frac{\lambda}{\delta\lambda} \approx 50000$, which is inadequate for measuring line bisectors as Gray did. Instead, we represent the absorption line profile as an expansion of Hermite polynomials. H_1 is absorbed into the line center position and H_2 is absorbed into the line width, leaving H_3 as the lowest order non-zero term in the expansion.

- The vanadium line is not present in the spectrum of τ Boo due to its higher photospheric temperature.

IV. Simulations

- **Simulations were run for all values of m and inclinations of 15, 45, and 75 degrees.**

- **The value of the motion vertical velocity, V_z, is arbitrarily chosen, and can be scaled so that the model output matches the observations. However, it should be noted that for the Sun $V_z \approx 20$ cm/s for individual p-modes, $V_z \approx 250$ cm/s for constructive interference of all the p-modes for the sun seen as a star, and $V_z \ll 20$ cm/s for individual g-modes.**

<u>51 Pegasi</u>

- **The simulations of 51 Pegasi show that the apparent radial velocity variations are a factor of 4 larger than the bisector span, though Gray reports a bisector span comparable to the radial velocity variations.**

- **If we scale our simulations by a factor of ~ 7 so the bisector span matches the amplitude reported by Gray, variations of the H_3 coefficient reach the 0.5% level. Our observations show no evidence of variations at this amplitude (Figure 1), but the noise level in the analysis to date is too high relative to the expected amplitude for a conclusive result.**

τ Boötis

- **The rapid rotation of τ Boo results in a higher ratio of bisector span velocity to apparent radial velocity than for 51 Pegasi – the line variations are only in the wings of the lines, primarily effecting the shallow segment of the line bisector.**

- **The amplitude of all the simulated parameters is much larger for τ Boo than for 51 Peg.**

- **If we scale our simulations by a factor of $\sim$ 1.8 so the apparent radial velocity matches the observed radial velocity, variations of the H_3 coefficient reach the 7% level. Our observations (Figure 6) rule out variations at this amplitude at a $\approx$ 20 σ confidence level.**

V. Conclusions

- Pulsations of Sun–like stars with periods of days would have to be the result of g-modes excited by some unknown process not present in the Sun, or the result of some unknown phenomena.
- Our results rule out the possibility of pulsations causing the radial velocity variations seen in τ Boo, leaving an orbiting companion as the most plausible conclusion
- Our results, while not conclusive, indicate that it is unlikely that pulsations are the cause of the radial velocity variations seen in 51 Peg. We believe that an orbiting companion is still most likely cause for the radial velocity variations in 51 Peg, but that further observations and analysis are required to definitively resolve this question.
- We hope to reduce the noise level in the H_3 coefficient values of the 51 Peg observations presented here by adding more spectral orders to the analysis.
- It is difficult to produce pulsations on Sun–like stars – such as 51 Peg – that would result in the apparent radial velocity observed or to produce the bisector span variations reported by Gray
- It would also be difficult to produce pulsations on a slowly rotating Sun–like star that would produce bisector span variations at the same level as apparent radial velocity changes