Leibniz-Institut für Astrophysik Potsdam

LARGE BINOCULAR TELESCOPE

PEPSI

The Potsdam Echelle Polarimetric and Spectroscopic Instrument

A chemical abundance analysis of the ancient planet-host star Kepler-444

C. E. Mack III, K. G. Strassmeier, I. Ilyin, F. Spada (AIP, Germany), and S. Schuler (University of Tampa, USA)

Abstract. We obtained a very high resolution and high S/N spectrum of the K0V multi-planet host Kepler-444. The spectrum has a resolution of up to R=250,000, a continuous wavelength coverage from 423 nm to 912 nm, and S/N ratio in the continuum of between 150–550:1 (blue to red). KEPLER photometry revealed five transiting planets with radii between those of Mercury and Venus and orbits within 0.1 AU of the star (i.e., within the orbit of Mercury). Perhaps even more astounding though is the old age of the host star of 11.2±1.0 Gyr from asteroseismology (Campante et al. 2015). These author's spectroscopic analysis of a Keck/HIRES spectrum (R=60,000, S/N ≈ 200) yielded Teff=5046 K and log g=4.6, as well as sub-solar abundances of Fe, Si, and Ti, leading to a moderately large [α/Fe] index of 0.26 dex. These results indicate that (low-mass) planet formation was already ongoing shortly after the universe was created and that the chemical composition of the protostellar material did not have to be metal rich. In addition, through our detailed chemical analysis of Kepler-444, we were able to estimate the typical Fe core mass fraction of its 5 known rocky planets.

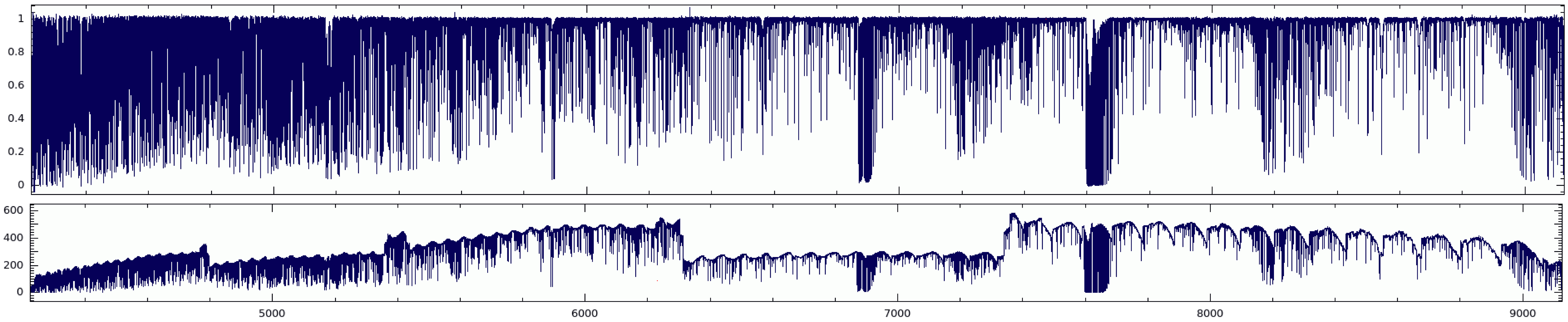
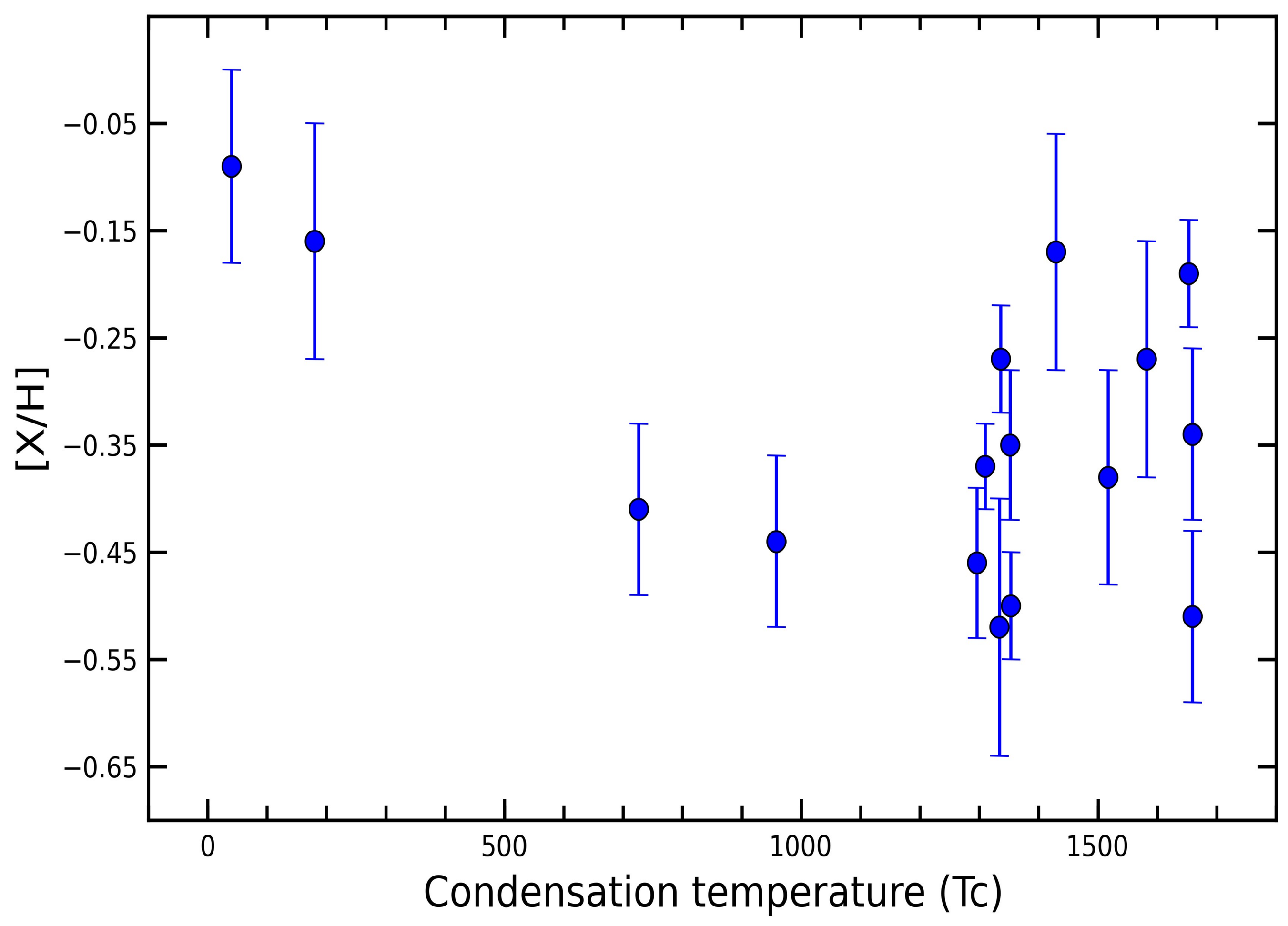
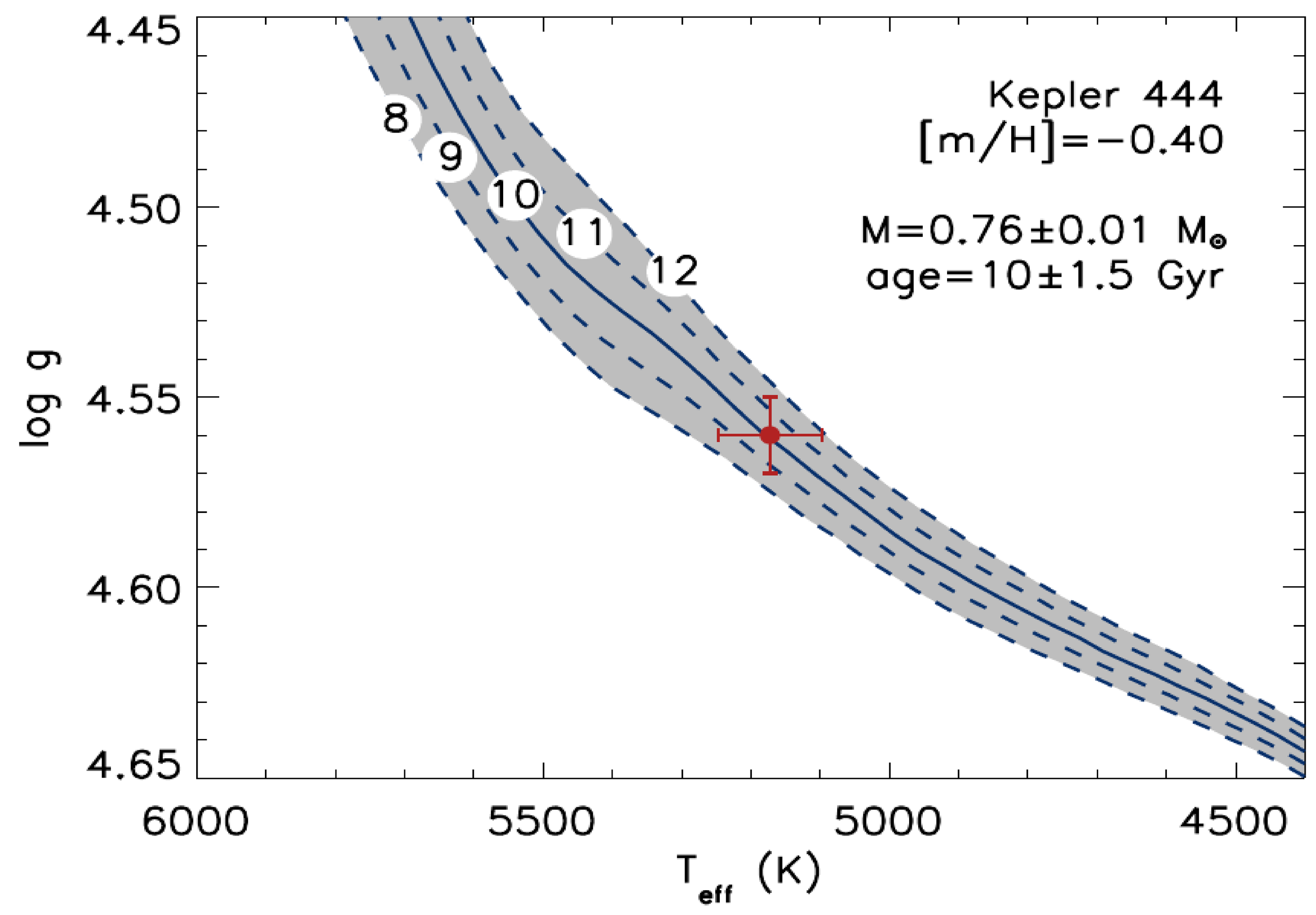


Fig. Top. Condensed view of the Kepler-444 deep PEPSI spectrum. The wavelength coverage is complete from 423 to 912 nm with an average dispersion of 10 mÅ/pix and average spectral resolution of 220,000. The bottom panel shows the S/N ratio per pixel. The deep spectrum is made up by 6-10 individual exposures, each typically 20min. Five of the six cross dispersers were employed. Note that there were less exposures for CD-V, seen in the middle with lower S/N.





The photospheric chemical abundances of Kepler-444. We performed a detailed spectroscopic analysis, and determined the chemical abundances of 16 different elements. We find no trend with condensation temperature (Tc) for the abundances of the refractory elements (Tc > 950 K). Furthermore, we determined the stellar parameters to be Teff=5172 +/- 75 K, log g=4.56 +/- 0.18 dex, and [Fe/H] = -0.52 +/- 0.12 dex. Our value for Teff differs from the Campante et al. value by 125 K, but they agree within the 2-sigma error bars. Our value for log g is in complete agreement with both the spectroscopic and asteroseismic log g value that Campante et al. determined, and our metallicity and [α/Fe] index of ~0.2 dex are also in good agreement.

Furthermore, from a simple chemical model described in Santos et al. (2015) – see equations below – it is possible to estimate the typical mass fraction of the Fe core of a rocky planet in the Kepler-444 system from the photospheric abundances of Mg, Si, and Fe. We find that the typical Fe core mass fraction, i.e., the ratio of the mass fraction of Fe to the total sum of the mass fractions of MgSiO3, Mg2SiO4, and Fe, is around 24%. This is significantly less than the ~30% typical Fe core mass fraction found in our more metal-rich solar system.

$$m_{\mathrm{H_2O,disk}} = m_{\mathrm{H}}\left(\frac{\mu_{\mathrm{H_2O}}}{\mu_{\mathrm{H}}}\right)\left[\frac{N_{\mathrm{O}}}{N_{\mathrm{H}}} - \frac{N_{\mathrm{Mg}}}{N_{\mathrm{H}}} - 2\cdot\frac{N_{\mathrm{Si}}}{N_{\mathrm{H}}}\right]$$

$$m_{\mathrm{MgSiO_3,disk}} = m_{\mathrm{H}}\left(\frac{\mu_{\mathrm{MgSiO_3}}}{\mu_{\mathrm{H}}}\right)\left[2\cdot\frac{N_{\mathrm{Si}}}{N_{\mathrm{H}}} - \frac{N_{\mathrm{Mg}}}{N_{\mathrm{H}}}\right]$$

$$m_{\mathrm{Mg_2SiO_4,disk}} = m_{\mathrm{H}}\left(\frac{\mu_{\mathrm{Mg_2SiO_4}}}{\mu_{\mathrm{H}}}\right)\left[\frac{N_{\mathrm{Mg}}}{N_{\mathrm{H}}} - \frac{N_{\mathrm{Si}}}{N_{\mathrm{H}}}\right]$$

$$m_{\mathrm{CH_4,disk}} = m_{\mathrm{H}}\left(\frac{\mu_{\mathrm{CH_4}}}{\mu_{\mathrm{H}}}\right)\frac{N_{\mathrm{C}}}{N_{\mathrm{H}}}$$

$$m_{\mathrm{Fe,disk}} = m_{\mathrm{H}}\left(\frac{\mu_{\mathrm{Fe}}}{\mu_{\mathrm{H}}}\right)\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}$$

The Age of Kepler-444. Using two independent age indicators, we find an age consistent with the one determined from asteroseismology. First, combining our spectroscopic values of Teff and log g with the Yale-Potsdam Isochrones (YaPSI: Spada et al. 2017), we found an age of 10 +/- 1.5 Gyr. Second, using gyrochronology (Barnes 2010) and the 49.4 +/- 6 day rotation period determined by Mazeh et al. (2015), we derived an age of 10.9 +/- 2.5 Gyr. Both our isochronal and gyro age are consistent with the asteroseismic age of 11.2 +/- 1.0 Gyr.

Conclusions. Kepler-444 is an ancient planetary system with an age of ~10-11 Gyr. In addition, the photosphere of Kepler-444 is metal-poor and alpha-enhanced. This implies that terrestrial planet formation was underway in just a few billion years after the universe formed, and further underscores the known trend that small planets do not have a special preference or need for metal-rich host stars (Sousa et al. 2011; Buchhave et al. 2012, 2014). However, the bulk composition and interior structure of terrestrial planets that form in metal-poor environments may be strikingly different from those that form in more metal-rich systems. Indeed, we estimate a typical Fe core mass fraction of 24% for Kepler-444's rocky planets, which is quite different from the typical value of 30% observed in the solar system.

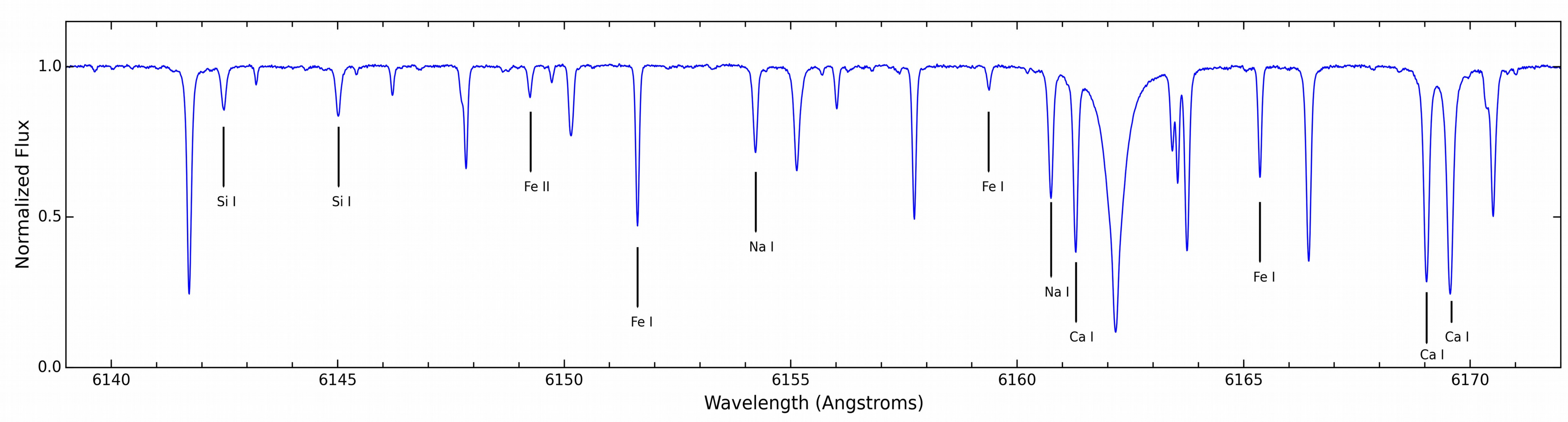


Fig. Kepler-444 spectral region between 6140Å and 6170Å. A selection of the lines measured in this region are labeled.

References.

Barnes, S. A. 2010, ApJ, 722, 222
Buchhave, L. A., Latham, D. W., Johansen, A., et al. 2012, Nature, 486, 375
Buchhave, L. A., Bizzarro, M., Latham, D. W., et al. 2014, Nature, 509, 593
Campante, T. L., Barclay, T., Swift, J. J. et al 2015, ApJ, 799, 170
Mazeh, T., Peters, H.B., McQuillan,A., & Goldstein, E. S. 2015, ApJ, 801, 3
Santos, N.C., Adibekyan, V., Mordasini, C., et al. 2015, A&A, 580, L13
Sousa, S. G., Santos, N. C., Israelian, G., Mayor, M., & Udry, S. 2011, A&A, 533, A141
Spada, F., Demarque, P., Kim, Y.-C., Boyajian, T. S., & Brewer, J. M. 2017, ApH, 838, 161

LBTO users meeting, Florence, June 20-23, 2017