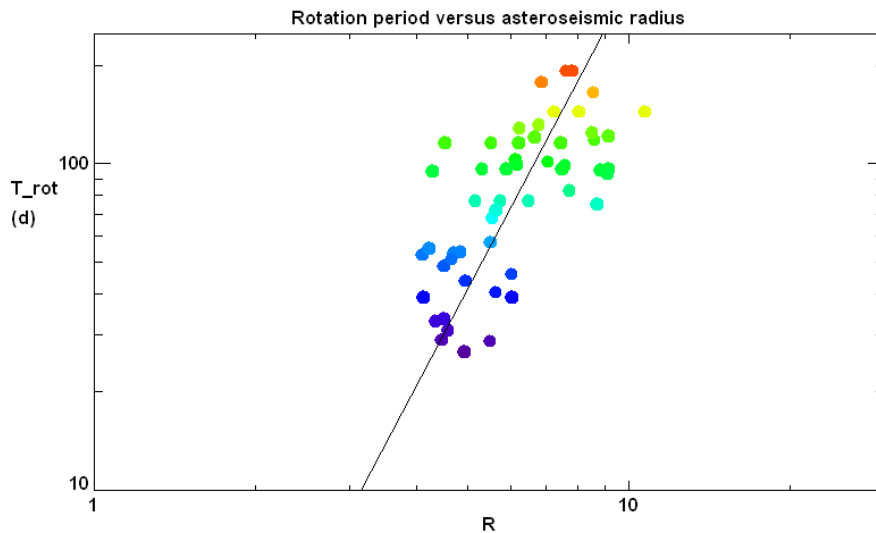


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## Red-giant rotational splittings

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*Aims : Analysis of the rotational splitting.*

*Methods : The mode and degree identification provided by the identification of the red-giant universal pattern allows us to point directly on the non-radial modes. The EACF is used to derive the rotational splittings of these modes, then the corresponding period of their g mode component.*

*Results : Rotational splittings are clearly identified. There is some evidence that these rotational splittings behave as p mode rotational splittings. This allows us to derive a rotation period. Then, a scaling law between this inferred rotation period and the stellar radius is put in evidence.*

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Red-giant pressure mode oscillations have been studied in detail. Now it is time to focus on the fine structure of the modes. In this report, we address the rotational splittings.

## 1. Method

The identification that *all* red-giants share the same homologous oscillation pattern, based on the determination of the function  $\varepsilon(\Delta\nu)$ , gives directly the complete identification of the pressure mode pattern (Mosser et al., A&A Letters in press).

The analysis of the rotational splittings of non-radial modes is performed thanks to the EACF (Mosser & Appourchaux 2009) with ultra-narrow filters.

We have searched for rotational splittings around both  $\ell = 1$  mixed modes and  $\ell = 2$  modes. In both cases, we suspect very slow rotation so that we suppose a simple rotational splitting of the form

$$\nu_{n,\ell,m} = \nu_{n,\ell,m} + m (1 - C) \delta\nu_{\text{rot}} \quad (1)$$

If differential rotation is neglected, we have  $C \simeq 0$  for p modes but  $C \simeq 1/\ell(\ell+1) = 1/2$  for g modes. Which  $C$  is OK for mixed modes? We propose an answer later.

## 2. Analysis

All RG observed up to Q4 have been analyzed. The criterion for a positive detection is the measure of the same  $\delta\nu_{\text{rot}}$  value (within error bars  $\simeq 20\%$  for an individual measure) in at least 4 frequency ranges centered on 4 different non-radial modes, with signature of the EACF above the threshold level (Mosser & Appourchaux 2009).

In order to avoid confusion with the spacings of g modes, only very tiny rotational splittings have been tested. In practical, we search only for splittings smaller than half the g mode spacing. Therefore, we only used ultra-narrow filters, with a width of the order of  $1 \mu\text{Hz}$  or less.

The conjugated effect of the tiny width of the filter and of the limited frequency resolution (about  $0.038 \mu\text{Hz}$  for the data up to Q4) makes the detection not precise, about 20-30%.

## 3. Results

### 3.1. Tests

All results found by the automated pipeline have been checked individually. Checks dealt with :

- Confusion between rotational splittings and mixed g mode patterns. They are a priori excluded by the method. However, the EACF is known to peak also harmonics of the spacings. As a result, about 1/4 of the raw results have been discarded since they were linked to the g mode spacing.
- Possible spurious results due to the speckle-like aspect of the modes have been discarded, when radial modes present the same complex pattern as non-radial modes.
- Possible confusion between  $\delta\nu_{\text{rot}}$  and  $2 \delta\nu_{\text{rot}}$  has been corrected, when possible.

### 3.2. Splittings

According to the examination of a few targets, the preferred value of  $C$  is 0 as for p mode, since  $C$  appears to have the same value for both  $\ell = 1$  and 2 multiplets. This will need a careful check on more targets. However,  $C \simeq 0$  appears clearly for a star as KIC 4952717 seen nearly edge-on.

For such a star, the measure of the rotational splitting gives  $2 \delta\nu_{\text{rot}}$  instead of  $\delta\nu_{\text{rot}}$ . This shows that the complete characterization of the splittings, including the stellar inclination  $i$ , is required to derive accurate rotation periods.

Due to frequency resolution, rotational splittings are preferentially identified in stars with  $\langle\Delta\nu\rangle$  greater than the peak of the clump value (Fig. 2). Examples of rotational multiplets are given in Fig. 1.

### 3.3. Period of rotation

We assume that we can derive a period of rotation  $T_{\text{rot}} = 1/\delta\nu_{\text{rot}}$ , with the coefficient  $C$  fixed to 0 as for p modes, solid rotation being assumed.

As expected, the period of rotation increases with increasing luminosity since the luminosity increases mainly with the stellar radius (Fig. 3). The relation between the period of rotation and the asteroseismic radius gives a scaling law as (Fig. 4) :

$$T_{\text{rot}} \propto R^{3.1 \pm 0.5} \quad (2)$$

The relation seems affected by the stellar mass, with, at fixed radius, a more rapid rotation for the more

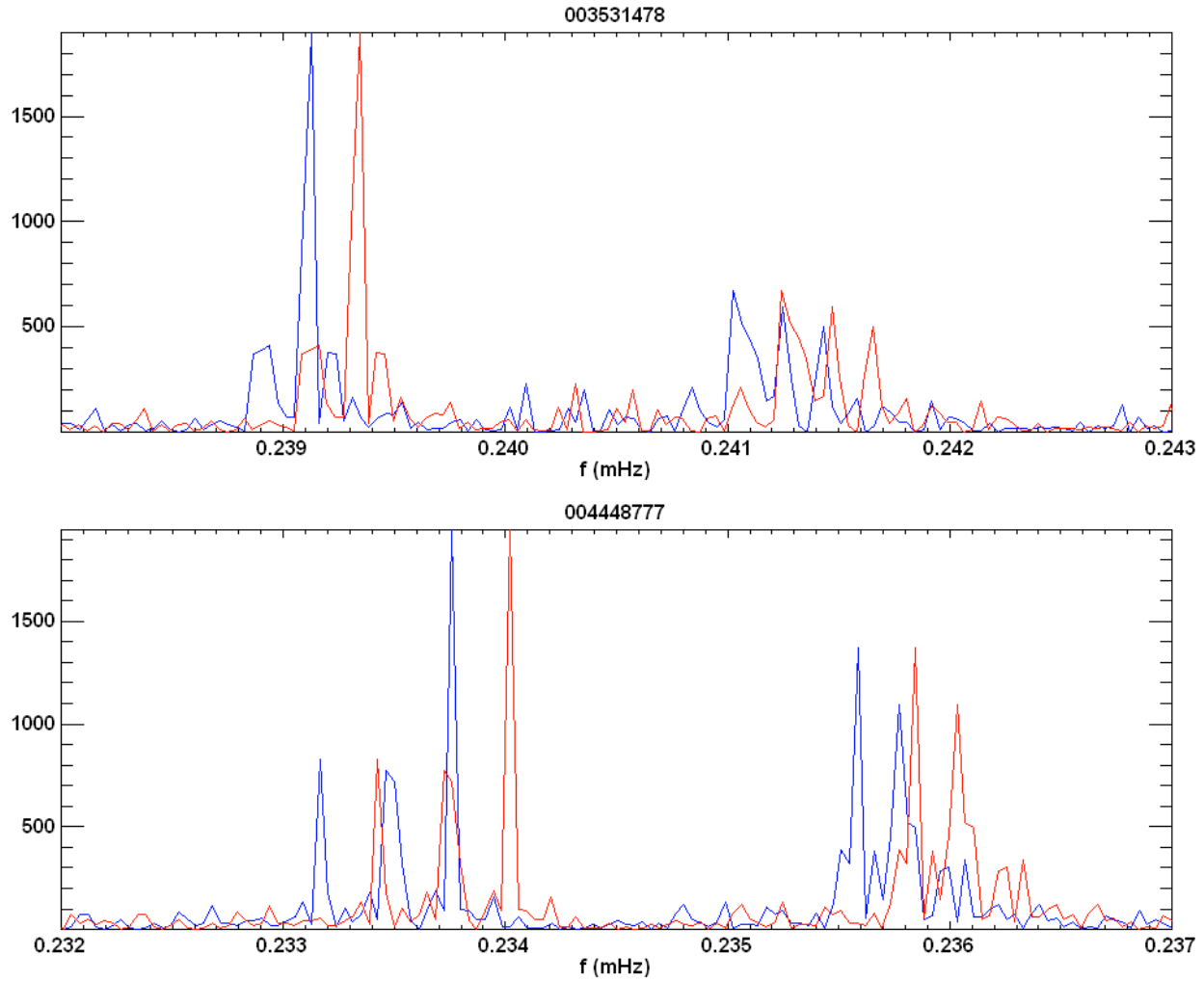


FIGURE 1 – A few examples of rotational multiplets, with a zoom on  $\ell = 1$  mixed modes. The shift between the blue and red spectra corresponds to the rotational frequency derived from the pipeline.

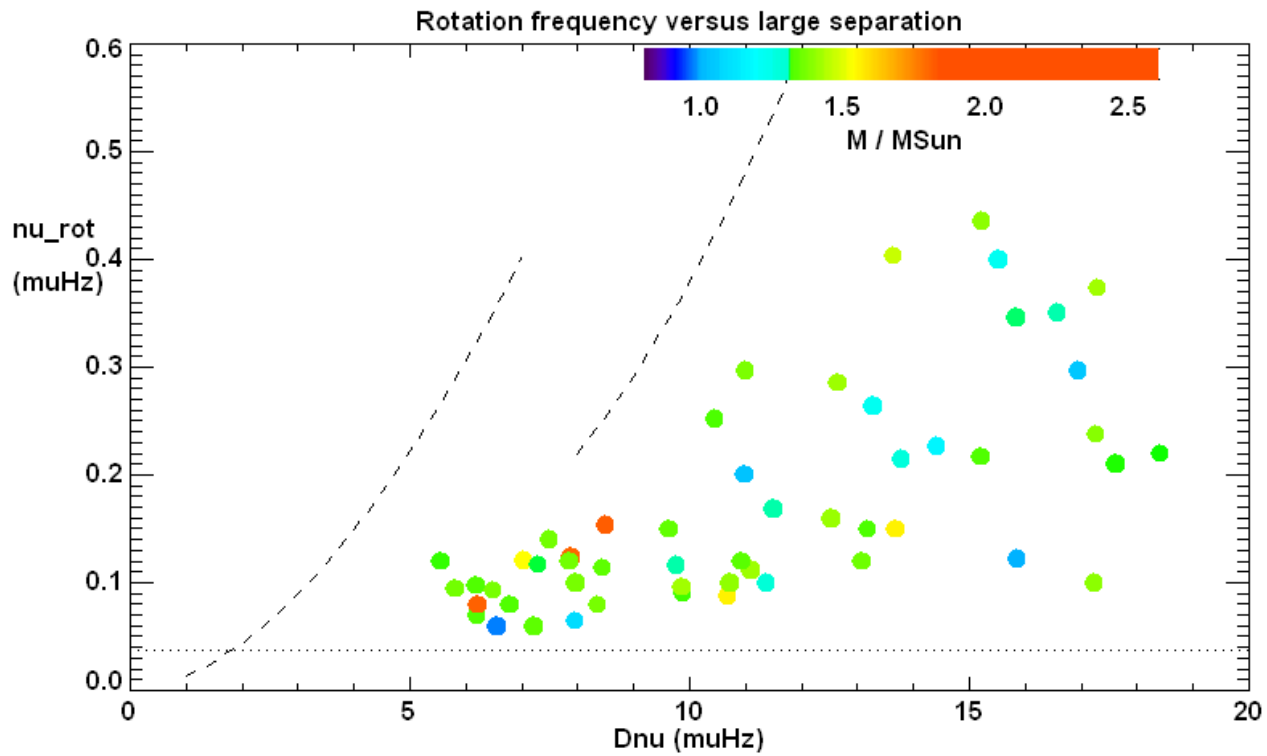


FIGURE 2 – Rotational splitting as a function of the large separation. The dotted line gives the frequency resolution. The dotted lines represent the confusion limit with mixed modes.

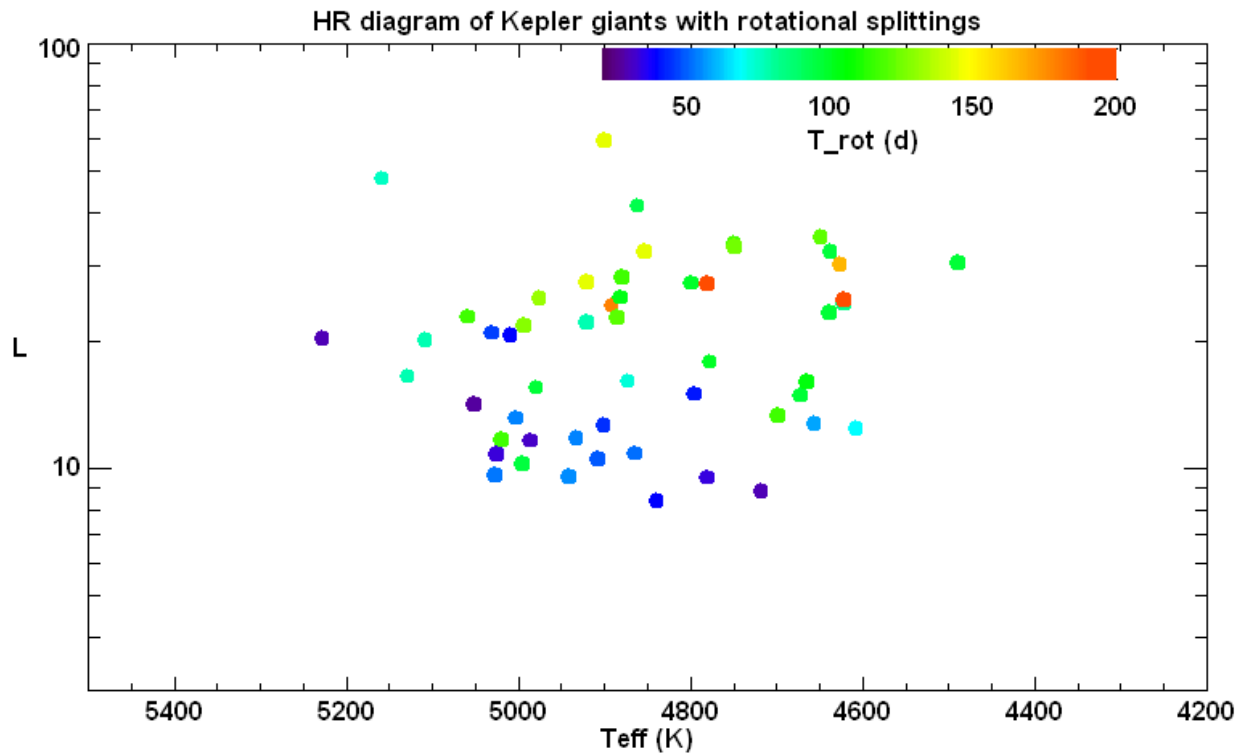


FIGURE 3 – HR diagram of the Kepler red giants with rotational splittings.

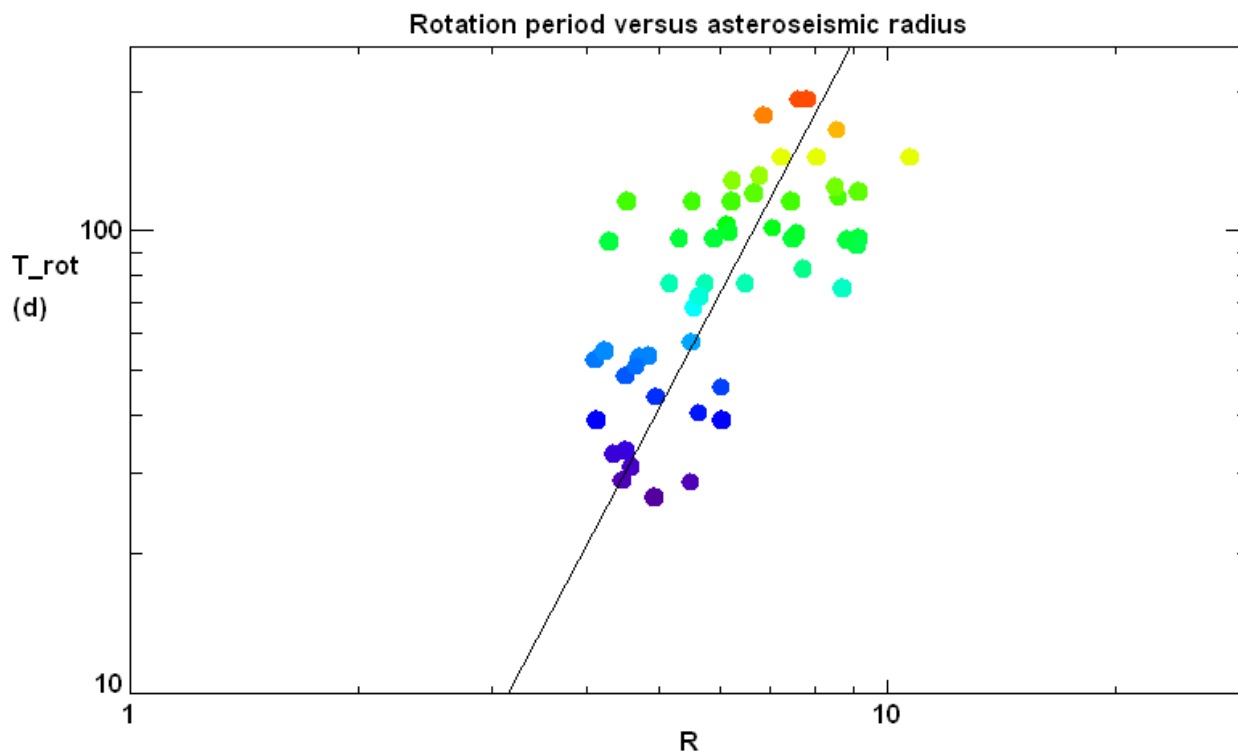


FIGURE 4 – Period of rotation versus asteroseismic stellar radius. Same color code as in Fig. 3. Large rotation periods correspond to large stellar radii.

massive stars (Fig. 5).

We can also derive an estimate of the rotational velocity. (Fig. 6).

## References

Mosser & Appourchaux 2009, A&A, 508, 877  
 Mosser et al., A&A Letters in press.  
 2010arXiv1011.1928M

## 4. Discussion

At this stage, rotational splittings are detected and confirmed in about 50 stars.

Including next *Kepler* quarters will help :

- to confirm this detection and enhance the precision of the measure of  $\delta\nu_{\text{rot}}$ .
- to extend the scaling law up to larger radii.
- to address rotation in the red clump-stars.
- to validate the influence of the mass and analyze its signification.
- to identify more precisely rotational multiplets and derive stellar inclinations.
- to measure  $C$ .

And more work needs to be done to insure that  $T_{\text{rot}} = 1/\delta\nu_{\text{rot}}$  can be seen as *the* period of rotation of the star. We nevertheless have now the tools.

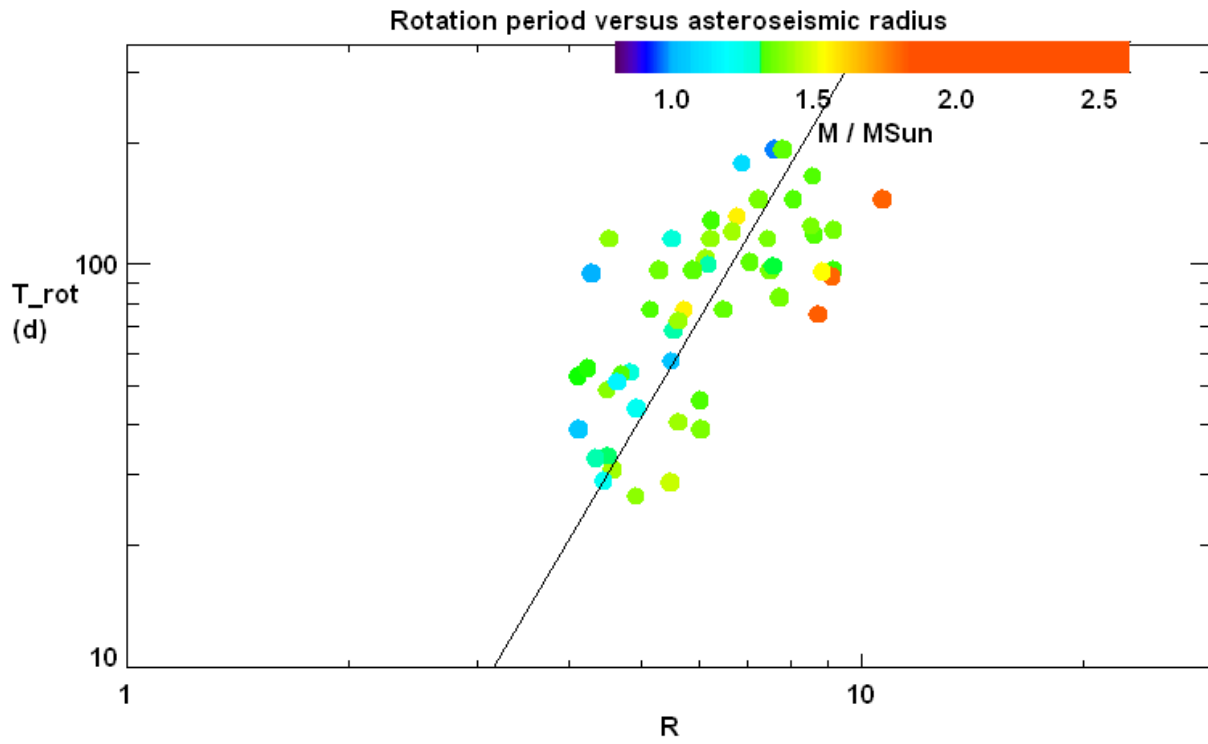


FIGURE 5 – Period of rotation versus asteroseismic stellar radius, with indication of the asteroseismic mass (according to the color code).

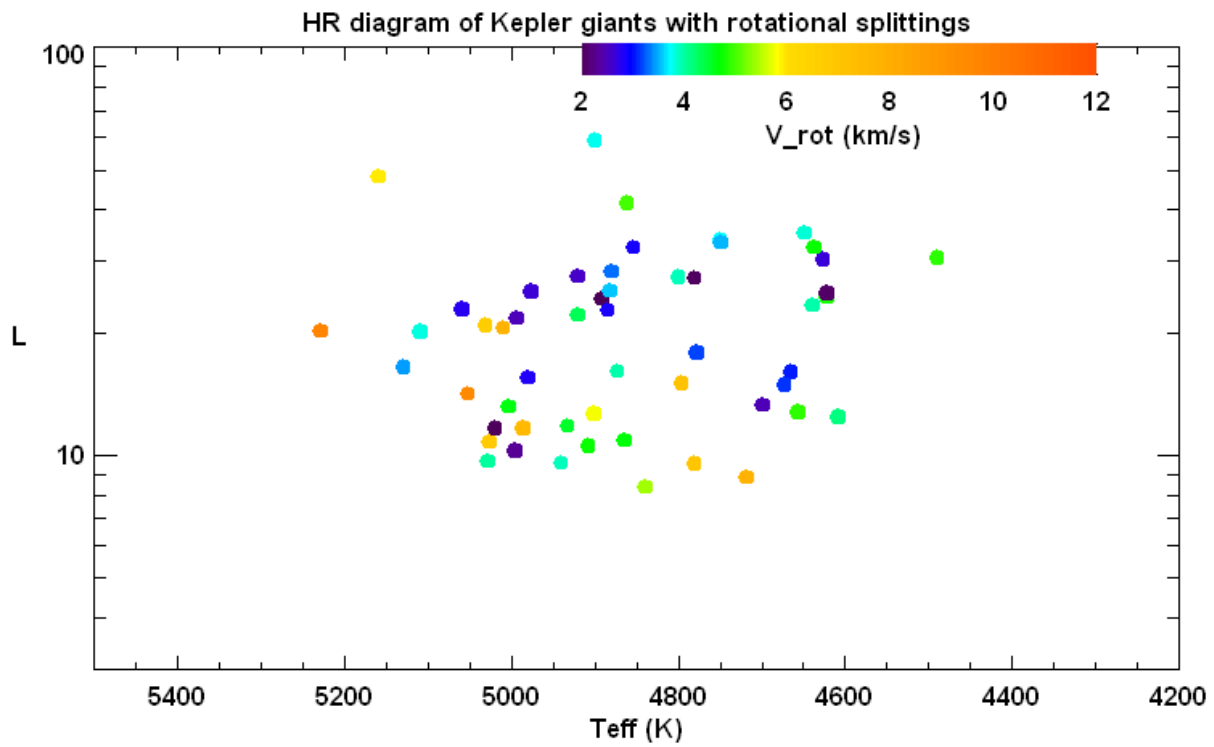


FIGURE 6 – HR diagram of the Kepler red giants with rotational velocities.