REFERENCES

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HYDROGEN CONVECTION ZONES AND STELLAR ROTATION

O. C. Wilson (1966) has recently made an interesting attempt to connect the rotation of stars with their chromospheric properties and presence of an outer convection zone. In particular, he finds the following:

1. The main-sequence stars with Strömgren colors $(b - y) > 0.30$ are slow rotators. He suggests that their rotation has been slowed down by a braking mechanism connected with their hydrogen convection zone. Schatzman (1962) has described one such mechanism.

2. The transition region on the main sequence between deep and shallow convective envelopes is narrow and occurs in the vicinity of spectral type F4. Wilson also points out that the boundary line between fast and slow rotators coincides approximately with the evolutionary track off the main sequence of an F4 star.

3. That chromospheric activity (measured by the presence of the H and K emission lines of Ca II), which is usually associated with the hydrogen convection zone, also terminates near spectral type F4 on the main sequence. Such activity is not observed along the upper edge of the main sequence (note the lack of points in Wilson’s Fig. 5 for $b - y < 0.33$, $c_i > 0.4$).

The purpose of this Note is to bring forth additional evidence supporting Wilson’s interpretation of his observations. It is drawn from recent calculations of stellar structure and bears on the position and shape of the boundary line between fast and slow rotators in the $c_i$ versus $(b - y)$ diagram, and on the observations of H and K emission features. Let us consider each of Wilson’s points in turn.

1. Main-sequence stellar models with the appropriate Population I chemical composition ($X = 0.67$, $Z = 0.03$) have been published by Demarque and Larson (1964). Inspection of their Tables 1 and 2 indicates that the transition to no convection zone is sudden. There is, however, some dependence of the log $T_{\text{eff}}$ at the transition point on the assumed mixing length to pressure scale height ratio $l/H$. For $l/H = 1$, the break occurs at log $T_{\text{eff}} = 3.823$ or spectral type F6 (Harris 1963). For $l/H = 1.6$, it occurs at log $T_{\text{eff}} = 3.85$ which corresponds to F2. Similar unpublished models for $X = 0.68$ and $Z = 0.03$ with $l/H = 1.6$ show a definite convection zone for a mass of $1.37 M_\odot$ and none for $1.41 M_\odot$ on the main sequence with a break at log $T_{\text{eff}} = 3.845$, in good agreement with the observations. This sharp transition has also been observed in the Hyades by Kraft (1965).

2. Wilson points out that the boundary line between fast rotators and slow rotators seems to coincide with an evolutionary track, using the models of Kelsall and Strömgren (1965). Since the Kelsall-Strömgren models really apply to more massive stars, we have used new results valid in the relevant mass range, from 1.2 to $1.4 M_\odot$. They include evolutionary tracks for $1.2 M_\odot$ (Hallgren and Demarque 1966), $1.4 M_\odot$ (Hallgren 1966) and a shorter track for $1.3 M_\odot$ obtained for the purpose of this paper. All three tracks were constructed under the assumption that $X = 0.67$, $Z = 0.03$ and...
The general shape of the three evolutionary tracks agrees with the observed boundary line between fast and slow rotators. The hook in the evolutionary track which is characteristic of the evolution of stars in this mass range is very pronounced in the \( c_1-(b-y) \) array. It represents a stage of rapid evolution and consequently should not be noticeable in the observations. At no point on the tracks for 1.4 and 1.3 \( M_\odot \) have models a convection zone, whereas the models for 1.2 \( M_\odot \) have a deep convection zone near the main sequence. Note that the 1.4 \( M_\odot \) model, which is slightly to the left of the zero-age main sequence, applies to a non-rotating star. Rotation would shift it to the right in the \( c_1-(b-y) \) diagram as can be inferred from the paper of Roxburgh and Strittmatter (1965).

3. It is also possible to advance a partial explanation for the dearth of stars exhibiting H and K emission near the upper edge of the main sequence, as noted by Wilson. It is probably a real effect due to the lack of a surface convection zone among stars in this part of the \( c_1-(b-y) \) diagram. The evolutionary track for 1.2 \( M_\odot \) shown in Figure 2 illustrates this point. From the main sequence until it reaches point \( B \), the star has a convection zone. At point \( B \), the convection zone vanishes until the star passes through point \( C \) when it reappears. The line joining the main-sequence position corresponding to the transition from convective to radiative surface (point \( A \)) and \( B \) and \( C \) agrees with the upper envelope of H and K activity, as deduced from the dots and crosses in Figure 2.

But our argument does not explain the lack of stars with H-K emission for later spectral types, below the dashed line of Figure 2. Wilson (1963) has suggested that there is a relation between H-K intensity and surface magnetic fields, in analogy with the
solar surface. It becomes then difficult to separate the relative importance of convection and magnetic fields on H-K intensity. It is likely, however, that surface magnetic fields and convection are not independent parameters, at least insofar as sunspot activity is concerned. Although late-type subgiants and giants are known to have deep convection zones, it is also recognized that convection is very inefficient there, a large fraction of the energy being transported by radiation in the low-density outer layers. The efficiency of the dynamo action may then be reduced, thus reducing magnetic activity. This tentative argument could indeed explain the lack of H-K emission observed by Wilson near the upper edge of the main sequence.

![Graph](image)

**Fig. 2.**—The dots, pluses, and crosses represent stars with H-K intensities of 1, 2, and 3, according to Wilson (1966). The evolutionary track for $1.2 \, M_\odot$ is also indicated. The dashed curve joins transition points between regions with and without convection zones, in the sense that models below the line have convection zones and models above the line do not.

Finally, it is interesting to note that the position of the dashed line is a function of the mixing length adopted in the construction of the models. One gets best agreement with Wilson’s data for $l/H = 1$, a value in agreement with that obtained by fitting model main sequences to the zero-age main sequence in the mass range from 1.2 to 1.4 $M_\odot$. If the suggestion of Hodge and Wallerstein (1966) regarding the distance modulus of the Hyades is accepted, then the $l/H$ ratio used by Demarque and Larson should be lowered, and may approximate unity even for masses below 1.2 $M_\odot$.

We are indebted to Dr. O. C. Wilson for reading the first draft of this Note and for making several suggestions. This work was supported by the National Research Council of Canada.

P. DEMARQUE*
R. C. ROEDER

August 1, 1966

DAVID DUNLAP OBSERVATORY
UNIVERSITY OF TORONTO

* Now at the University of Chicago.
THE BEHAVIOR OF RU CAMELOPARDALIS AS AN EXAMPLE OF OSCILLATION HYSTERESIS

During an interval of several months in 1964, the variable star RU Cam virtually ceased its pulsation. A detailed study of the history of this star is in preparation, but for present purposes the results can be summarized very simply. RU Cam had been observed as a variable star on photographic plates exposed as early as 1899, and although it has been difficult to classify unambiguously, this star had several of the characteristics of W Virginis stars. Its period of 22 days showed slight fluctuations, but its light-curve was quite stable, and the phase relation between light and velocity variation is typical of W Virginis stars.

The most strikingly abnormal feature of RU Cam was that its color and spectral type corresponded to a much lower temperature than is typical for variables with \( P = 22 \) d. Its spectrum at minimum light showed carbon features, making it unique among variables for this period.

The present Note comments qualitatively on the abrupt cessation of pulsation. Any theory for this cessation must account explicitly for the very short time scale of the phenomenon. The mean brightness and color of this star have not changed detectably during the past several decades. Therefore, its amplitude of pulsation had evidently been an extremely sensitive function of some parameter characterizing the star's structure. Linearized analyses of pulsational instability have not shown any such extreme sensitivity, and they would rather imply a substantial evolutionary change to produce such a large change of amplitude. Of course, linearized theory cannot treat directly the stationary amplitude of developed pulsations, so such analyses will not solve the present problem.

Considered as a non-linear oscillator, RU Cam has behaved like a pendulum clock, which is subject to oscillation hysteresis. This phenomenon has been discussed in detail by Bogoliubov and Mitropolsky (1961), and it seems to give qualitative understanding of the behavior of RU Cam. Briefly stated, a pendulum clock with an escapement is a mechanical system that is stable against small-amplitude oscillations but for which periodic large-amplitude oscillations may be sustained as a limit cycle. (The van der Pol oscillator in its usual form is not an example of this sort of behavior, because it is not stable against small-amplitude oscillations.) We therefore suggest that, as RU Cam evolved, a slight modification of its interior “escapement mechanism” has finally stabilized it against large-amplitude oscillations, and that the amplitude decreased very rapidly, in a time scale much shorter than any evolutionary time scale, because the star was already stable against small-amplitude oscillations.