ROTATIONAL STUDIES OF LOWER MAIN SEQUENCE STARS

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I. Introduction

This review summarizes the techniques and limitations involved in determining small rotational velocities in late-type stars. Recent results from photoelectric line profiles of field main sequence G stars will also be presented.

Historically three techniques have been used to measure stellar rotational velocities: (1.) calibration of a "clean" line width in terms of computed profile models, (2.) use of the Fourier transform frequency domain (dissection of rotation and turbulent velocity fields from the thermal profile), and (3.) monitoring of the rotational modulation of a chromospherically active or spotted star. The results discussed below concern technique (2.). Technique (3.) has not been exploited much yet but holds considerable promise for the future, in particular for the measurement of ultra-slow rotation.

II. The Measurement Technique and Limitations

The Fourier dissection approach treats an individual unblended line, preferably on the shoulder of the curve-of-growth. The data transform is used to separate out rotation signatures, a boxy main lobe and a series of regular zeroes and sidelobes, from the remaining thermal and turbulent components. To do this, one computes a flux profile broadens it by appropriate amounts of macroturbulence and rotation, and fits the result to the observations in the frequency domain (Smith 1978). Down to velocities of about 10 km s^{-1} one may utilize the first zero sidelobe in the data transform to determine V_R sin i with considerable precision. For smaller velocities these signatures drop into the noise and can no longer be recovered. Then one can proceed only after adopting an accurate model of the macroturbulence velocity distribution. In our work the radial-tangential macroturbulence (Gray 1976) is used. This model produces no sidelobes and a rather pointed main lobe. For the measurement of small rotational velocities one can still make use of how rounded the main lobe of the transform is to determine the rela-

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tive importance of rotation and macroturbulence. This procedure is adequate but provides far less leverage on the solution than does the location of the sidelobe/zero at high velocities.

The most important error sources in rotational velocity measurement are: (1.) the uncertainty in continuum placement (even with data obtained from a multi-element detector), (2.) the difficulty of finding a line with "clean" wings up to the continuum, and (3.) uncertainties in the $T(\tau)$ relation used to compute an unbroadened model profile. Apart from these primary error sources there are a variety of second order error sources arising from uncertainties in the models of the competing broadening agents (the micro/macro-turbulences). Even if these problems could be brought under control, one would still run into a practical ultimate limit when the rotational and line width velocities become comparable. This limit occurs because at the lower Fourier frequencies the rotation transform is flat and it is difficult to detect "rotational filtering" of the data transform. This problem is greatly amplified at the larger frequencies one would like to use for rotational leverage because the data transform drops exponentially into the noise. As a result of these twin problems even large gains in the observational S/N ratio do not recover the data transform to much higher frequencies, which is what is needed to measure smaller velocities. The practical limit imposed by these realities is 2 to 2.5 km s^{-1}. This author is pessimistic about extracting smaller velocities by line broadening analysis techniques in the future. To determine still smaller velocities it will be necessary to monitor stars over long timescales to measure the rotational modulation of "active" lines.

III. Results

A comparison of two authors results (Smith 1978, Smith and Dominy 1979, Gray 1977, Gray and Martin 1979) indicates that rotational measurements can indeed be made in solar-like stars. For example, Gray and Smith find $V_R \sin i \doteq 1.9$ and 2.2 km s^{-1} from an analysis of solar lines, a result in excellent agreement with the correct value (1.8 km s^{-1}). The mean velocity of a group of four K giants in common to their studies is in agreement to ± 0.1 km s^{-1}. Finally, the rotational velocity for α Tau deduced by the 350-day modulation of the K2 line reported by Deutsch (1970) is 3.6 km s^{-1}, in reasonable agreement with the SD79 result of 2.7 km s^{-1}.

The available rotational velocities for main sequence stars were taken from S78 and S79 and divided into four rough age groups. Mean velocities were then computed for each age group and plotted. A similar procedure was employed to preliminary results of Soderblom's (1980) work. The results in Fig. 1 demonstrate the validity of the Skumanich (1972) $t^{-\frac{1}{2}}$ rotational-decay law over an age range of 30. This law is compatible with a solar core rotating more rapidly than the surface (Dicke 1972), but perhaps only to a moderate degree.

The intercept of the new relation depicted in Fig. 1 is 80% higher than the original Skumanich (1972) relation. When account is taken of inclination, one finds that the Sun's velocity is only 40% of the average value for stars of its age (Fig. 1, short dashes). This finding is confirmed by a velocity histogram (Fig. 2) when velocities are plotted in terms of their group modal values. From this histogram one sees that the Sun falls in the low 4 to 10%-tile of the rotational velocity distribution for all G stars, a result of potential significance in two ways:

1.) The present abnormally low rotation rate for the Sun implies a low initial rate for the proto-Sun, suggesting that the angular momentum distribution in the solar system is abnormal. In particular, other stars may have distributed their angular momentum in fewer outer Jupiter-sized planets.

2.) Slow rotation implies a quiet stellar chromosphere. Indeed Blanco et al. (1974) have already reported that the K2-feature falls below the intensity-age relation for stars. Recent IUE spectra of the Mg II k line by Basri and Linsky (1980) also show that the Sun is chromospherically quiet, compared to most other intermediate-age stars. This fact may have important ramifications for the ability of life to develop in the biological zones around other stars because flares from chromospherically active regions may produce too much x-ray and UV flux, and therefore biological mutations, to allow biological species to stabilize and to evolve to complex, sentient beings. At the very least, the search for extraterrestrial life should be concentrated to slowly rotating, metal-normal stars as, rare as they may be.

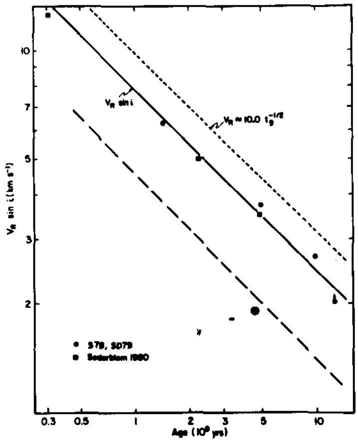

Fig. 1 - The rotation age relation for field G dwarfs and subgiants.

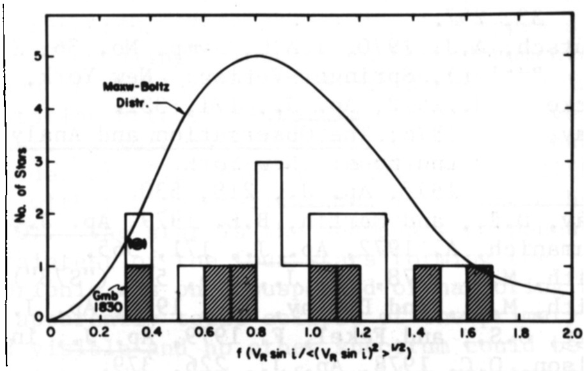

Fig. 2 - The rotational velocity histogram for Smith's stars in Fig. 1.

A comparison of our rotational velocities and Wilson's (1978) extensive search for sunspot cycles reveals no correlation. For example, the r.m.s. scatter about the mean period (~ 9 yrs.) in his data is only about 11%, whereas the scatter in rotational velocities is about 50%. Furthermore, rapid rotators (6 km s^{-1}) and slow rotators (Gmb 1830) have the same sunspot cycle length. Both arguments suggest the preliminary conclusion that solar activity cycles are insensitive to the rotational velocity -- an unexpected result.

Finally, it can now be stated that BY Dra and EQ Vir, two spotted flare stars, are more rapidly rotating than less active stars (Vogt and Fekel 1979, Anderson *et al.* 1977). This result extends the rotation-activity correlation up to 18 km s^{-1}, at least, and implies that this relation continues up to the highly active RS CVn stars as well.

IV. Desiderata

A list of rotational studies for the early 1980's should include the following: (1.) confirmation of the rotation-activity relation on an individual star-by-star basis, (2.) a long-term program to monitor rotational modulation (H2/K2, λ10830?), (3.) a clearer definition of the onset of rotational synchronism in binaries, (4.) a comparison of rotational velocities determined both by line broadening and modulation techniques. The future holds considerable promise for research in these areas thanks to the increasing availability of electronic silicon-array detectors.

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