DETERMINATION OF STELLAR ROTATIONAL VELOCITIES

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ABSTRACT. The three basic methods for measuring axial rotation of stars had been suggested before the beginning of this century. These are (1) Modulation of starlight due to dark or bright areas on a rotating star; (2) Distortions in the radial velocity curves of eclipsing binary systems; and (3) Line profile analysis. Research in each of these areas is reviewed.

1. INTRODUCTION

"If I may give my own opinion to a friend and patron, I shall say that the solar spots are produced and dissolve upon the surface of the Sun and are contiguous to it, while the Sun, rotating upon its axis in about one lunar month, carries them along . . . ." So wrote Galileo (Drake 1957) in his letter of May 4, 1612 to the wealthy Augsburg merchant and enthusiastic amateur of science, Mark Welser. Here we have the first determination of the rotation period of a star. But over 300 years were to pass before the next determination of a stellar rotational velocity. It is interesting, however, that the three basic methods for measuring stellar rotation had all been suggested, although not yet carried out, before the end of the last century.

As early as 1667, Bouillaud suggested that stellar variability was a direct consequence of axial rotation, the rotating star showing alternately its bright (unspotted) and dark (spotted) hemispheres, an idea which was further explored by Cassini, Fontenelle, and Miraldi (cf. Brunet 1931). More recently, Pickering (1881), in a study of variable stars, concluded that "The most natural explanation of the variation of a star of short period is that it is due to its rotation around its axis". Furthermore, "The difference in brightness of the two sides of a star may be due to spots like those of our Sun, to large dark patches, or to a difference in temperature". Pickering erred in trying to apply these ideas to close binary systems and Cepheid variables, but in recent years, periodic variations in light due to starspots and stellar plages have been used to determine rotation periods for certain classes of stars. Line profile analysis was first

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introduced in 1877, when Abney suggested that the effect of a star's rotation on its spectrum would be to broaden all of the lines and that ". . . other conditions being known, the mean velocity of rotation might be calculated." The third basic method for determining stellar rotational velocities was apparently first suggested by Holt (1893): ". . . in the case of variable stars, like Algol, where the diminution of light is supposed to be due to the interposition of a dark companion, it seems to me there ought to be a spectroscopic difference between the light at the commencement of the minimum phase, and that of the end, inasmuch as different portions of the edge would be obscured. In fact, during the progress of the partial eclipse, there should be a shift in the position of the lines; and although this shift is probably very small, it ought to be detected by a powerful instrument." This predicted distortion of the radial velocity curve of an eclipsing binary, sometimes called the "Rossiter Effect", was indeed detected less than 20 years later, and resulted some years after in the first actual measurements of stellar rotation since the observations of Galileo.

The aforementioned three methods of determining stellar rotational velocities will be discussed in this review. I should like to emphasize that the review will be limited to observational work only -- there exists an enormous literature concerning the theoretical aspects of stellar rotation which will not be included here. Furthermore, it would be impossible even to include all of the references to measurements of stellar rotation in a paper of this length. Therefore, whenever possible, I have referred to review papers with extensive bibliographies of earlier work rather than repeat long lists of references. Some of these, which have been very helpful in preparing this paper, are by Struve (1945), Huang and Struve (1960), Kraft (1969, 1970), and Moss and Smith (1981). In addition, two books on stellar rotation have appeared: The proceedings of IAU Colloquium No. 4 (ed. Slettebak, 1970a) and "Theory of Rotating Stars" (Tassoul, 1978). The latter is a superb contribution, with many references to both observational and theoretical papers.

2. METHODS FOR THE DETERMINATION OF ROTATIONAL VELOCITIES

2.1. Rotational Modulation

Although stellar disks generally cannot be seen beyond the sun, a rotating non-uniform disk should produce periodic changes in light which, if detectable, would permit determination of the period of rotation. Perhaps the first convincing detections of this kind were by Kron (1947, 1952), who found evidence in the light curves of the eclipsing binaries AR Lac and YY Gem for a patchy, non-uniform surface of the stellar components. Subsequent work generally divides into two categories: (1) photometry of a variable continuous spectrum as starspots appear and disappear on the rotating disk, and (2) measurements of the variation in strength of emission lines (e.g., Ca II H and K) which arise in plages in a rotating chromosphere. A large literature has developed in the last decade or so, and I will discuss only selected objects and papers.

2.1.1. BY Dra Stars. These are defined as UV Cet flare stars of spectral types dKe and dMe which, outside of periods of flaring, show periodic variations in light of several tenths of a magnitude, attributable to large, cool starspots on their surfaces.

Following Chugainov's (1966) discovery of periodic light variability in Popper's flare star HDE 234677, Krzeminski and Kraft (1967) using UBV photometry found similar variations in brightness in three dKe-dMe stars and ". . . agree with Chugainov that the most promising model appears to be the rotational modulation of a star with a non-uniform distribution of surface brightness". Krzeminski (1969) reached the same conclusion, finding equatorial rotational velocities of 10 and 15 km/sec for two of his stars. Upper limits to flare star rotational velocities were estimated by Gershberg (1970) to be 25-30 km/sec, based on flare statistics and Hα emission widths in four UV Cet stars. Bopp and Evans (1973) developed a model for the spots on BY Dra, based on 1965 and 1966 photometry, showing that "The spots must be large, covering up to 20 percent of the stellar hemisphere". Observations by Vogt (1975) in 1973 for this star were found to be inconsistent with a thermal dark spot model but explainable in terms of Ca II emission regions or plages. More recently, Pettersen (1980) observed sinusoidal variations in the magnitude of EV Lac outside of flares, interpreted these as due to intensity modulations from a photospheric spot group, and estimated an equatorial rotational velocity of 4.2 km/sec for this dM4.5e star. Many more references can be found in the review paper by Vogt (1983).

2.1.2. RS CVn Binaries and FK Com Stars. RS CVn binaries have been defined by Hall (1976) as "binaries with orbital periods between 1 day and 2 weeks, with the hotter component F-G V-IV, and with strong H and K emission seen in the spectrum outside eclipse". In 1972, Hall suggested that a model in which ". . . a region of tremendous sunspot activity darkens one side of the cool star", assuming synchronous rotation, can reproduce the many photometric complications observed in RS CVn. Recent studies of starspots and rotations of the components of RS CVn systems include those by Ramsey and Nations (1980), Vogt (1981), Guinan et al. (1982), and Fekel (1983), plus the references therein.

Another class of stars with photometric and spectral properties similar to those of the RS CVn binaries and BY Dra stars are the FK Com stars. These are apparently single G2-K0 giants with unusually large rotational velocities for their types (v sin i ≃ 100 km/sec), whose photometric variability can best be interpreted in terms of starspots (cf. Bopp and Stencel 1981; Holtzman and Nations 1984; Dorren et al. 1984).

2.1.3. Photometric Variations of Pre-Main-Sequence and Pleiades K Stars. Four pre-main-sequence K stars in the direction of the Taurus dark cloud complex were monitored with UBVRI photometry by Rydgren and Vrba (1983) and found to show quasi-sinusoidal light variations "apparently due to the presence of large starspots". The periods, which range from 1.9 to 4.1 days, correspond to rotational velocities of 75 to 20 km/sec. Van Leeuwen and Alphenaar (1983) observed 19 late G and early K-type members of the Pleiades cluster, finding all to be variable and 12 with semi-regular light curves like those of the BY Dra stars. If the variations are assumed to be due to rotational modulation, the corresponding rotational velocities are consistent with v sin i values of 75-150 km/sec found spectroscopically for two of the stars.

2.1.4. Chromospheric Variations in Lower Main-Sequence Stars. Wilson (1978) was the first to study the variation with time of the chromospheric activity in main-sequence stars. He measured fluxes at the centers of the Ca II H and K lines in 91 F5-M2 stars for time intervals of 9-11 years, but stated that "the data points are too few to establish short-term periodicities such as rotational modulation". Stimets and Giles (1980) analyzed his data for periodicities using an autocorrelation technique, however, and determined rotational periods for 10 stars, ranging between 2 and 37 days. Meanwhile, new H and K flux observations of 47 lower main sequence and eight evolved stars were made over a nearly continuous 14-week observing run and discussed by Vaughan et al. (1981) and Baliunas et al. (1983). These investigators ". . . find rotation rates easily for the main-sequence stars with strong emission or those later than about spectral type K0. With this technique, rotation rates can be measured precisely for the first time for equatorial velocities as slow as 1 km/sec, and independently of the aspect of the rotation axis".

Radick et al. (1983) studied the photometric variability of solar-type stars. Although their time resolution was not sufficient to obtain rotation periods, they point out ". . . the possible ability of photometric observations to measure stellar rotation should not be overlooked. Continuum photometry probably is sensitive mainly to dark spots, whereas the chromosphere diagnostics characterize the surrounding plage regions. However, for the Sun, spots are confined, both individually and as groups, to a much narrower range of latitudes than are the plage regions. Accordingly, spot-derived rotation periods may be more precise".

Lambert and O'Brien (1983) detected a marked variation of the chromospheric He I D_3 line at 5876 Å in the spectrum of the G5V star κ Cet, which they attribute to rotational modulation. The rotational velocity of κ Cet is estimated to be 3.9 km/sec on the basis of an 8.5 day period and an assumed radius $R_* \simeq 0.9 R_\odot$.

Ultraviolet studies of F, G, and K main-sequence stars with the IUE satellite by Blanco et al. (1979), Hallam and Wolff (1981), and Boesgaard and Simon (1982) have also revealed periodic variations in a number of chromospheric lines, which these investigators attribute to rotational modulation.

2.1.5. Ap Stars. It was Babcock (1949) who first considered ". . .the alternative hypothesis that the spectrum variables of type A are stars in which the magnetic axis is more or less highly inclined to the axis of rotation and that the period of magnetic and spectral variation is merely the period of rotation of the star". Deutsch's (1952, 1956) discovery of an inverse relation between the periods of Ap stars and the widths of their absorption lines supported this suggestion and led him to conclude that ". . . in the spectrum variables we observe the rotation of A stars that exhibit intensely magnetic areas, within which the peculiar line strengths are produced". Many studies of the spectrum and magnetic variables of type A exist, including several symposia devoted to these objects (e.g., Cameron 1967; Weiss et al. 1976; Liège Astrophys. Colloq. 23, 1981). A catalog of observed periods for Ap stars, with an extensive bibliography, was recently published by Catalano and Renson (1984).

2.1.6. Be Stars. Hutchings (1970) found a period of 0.7 days in the peak separation and V/R ratio of the double emission profiles of Hγ and Hβ in the spectrum of the B0 IVe star γ Cas, which he attributed to rotation. His observations show considerable scatter, however, and have not been confirmed as yet. Slettebak and Snow (1978) searched for rotational modulation of the Si IV and Mg II resonance doublets during 64 nearly-continuous hours of *Copernicus* observations of γ Cas but found no evidence for a rotation period. Most recently, Walker et al. (1979) reported velocity variation in the He I 6678 Å line in the spectrum of the rapidly-rotating 09.5 V star ζ Oph which they suggested to be consistent with non-unformities in stellar surface brightness being carried across the line of sight by rotation. In a later paper (Walker et al. 1981), however, they state that the observed features move too rapidly and linearly to be due to irregularities on the stellar surface itself, and suggest that an interpretation in terms of non-radial pulsations coupled with rotation cannot be ruled out. The latter interpretation was supported by a recent study of ζ Oph by Vogt and Penrod (1983). At this time, therefore, no unassailable evidence for rotational modulation has been found for Be stars.

2.2. Distortions in the Radial Velocity Curves of Eclipsing Binary Systems.

Following Holt's (1893) prediction, the first observational evidence for a rotational effect in the radial velocity curve of an eclipsing binary system was presented by Schlesinger in 1909 for the Algol variable δ Lib. In his words, "The rotation of the bright star has another consequence in certain parts of the orbit. In general we obtain light from the whole disk and the observed velocity is equal to that of the center of the star. Just before and just after light minimum, however, this is not the case; before minimum the bright star is moving away from us and part of its disk is hidden by the dark star. The part that remains visible has on the whole an additional motion away from us on account of the rotation; the observed velocity will therefore be greater than the orbital. On the other hand just after minimum the circumstances are reversed so that the observed velocity is less than the orbital". Forbes (1911) suggested that this effect could be used to measure equatorial rotational velocities, but Schlesinger (1911) replied that because of unknown limb-darkening effects, ". . .it would appear to be well-nigh hopeless, with present-day appliances at least, to attempt to determine . . . the rate of rotation from observational material alone". Schlesinger (1913) found the effect again in the radial velocity curve of λ Tau, as did Hellerich (1922) for a number of Algol-type variables. The first actual measurement of the rotational effect was by Rossiter (1924), who found a total range of 26 km/sec in the brighter component of β Lyr. He pointed out in this work that this rotational effect ". . . does not represent the value of the velocity of rotation at the limb of the star but represents only a fractional part of it. The magnitude of the effect depends on how much the light from the unbalanced visible limb is able to displace the apparent center of the line from the point where it would normally be measured". Soon thereafter, McLaughlin (1924, 1926) discussed the effect in Algol and in λ Tau, while Plaskett (1926) showed it to be present in 21 Cas.

In an important paper, Struve and Elvey (1931), assuming a rotational velocity derived from line broadening of 60 km/sec for Algol, showed that asymmetrical line profiles computed as the star goes in and out of eclipse agreed well with observed line profiles at those phases. They were able to derive the rotational effect in the radial velocities of Algol and show that it agreed well with McLaughlin's (1924) observations, thereby establishing the rotational velocity at about 60 km/sec.

McLaughlin (1933, 1934) computed "rotation factors" (the distances of the center of light of the luminous area from the center of the disk, expressed in units of the radius of the disk) from the photometric elements of four eclipsing binary systems and applied them to the observed rotational distortions in the radial velocity curves to obtain v sin i's for the principal components. He obtained 42 km/sec for Algol, 42 km/sec for λ Tau, 60 km/sec for δ Lib, and 200 km/sec for α CrB. These values may be compared with v sin i's determined from line-profile analysis of the same stars (Uesugi and Fukuda 1982): Algol, 55 km/sec; λ Tau, 85 km/sec; δ Lib, 75 km/sec; and α CrB, 135 km/sec. Kopal (1942), who included limb-darkening in his analysis, obtained v sin i = 48 km/sec from McLaughlin's (1934) radial velocity data for Algol -- somewhat closer to the value from line-profile analysis. Struve (1944) found a very large rotation effect in the partial phases of the eclipse of the B8 component of U Cep, from which he concluded that its equatorial velocity of rotation is 200 km/sec. After correcting the radial velocity measurements for asymmetries displayed by the Balmer lines, Hardie (1950) found a rotation effect of 250 km/sec for the same star, whereas Olson (1968) obtained v sin i = 310 km/sec from line profile widths. Many other examples of radial velocity curve distortions due to rotation exist: Struve (1950) estimated that the phenomenon had been observed in about 100 systems by 1949. A recent study is by Wilson and Twigg (1980).

2.3. Line Profile Analysis

2.3.1. Profile Fitting and Line-Width Measurements. After Abney's (1877) suggestion, Schlesinger (1909) seems to have been the first to call attention to rotational line broadening. Noting that "In close spectroscopic binaries like δ Lib the periods of rotation of the two stars are doubtless the same as the time of revolution", he suggested that "This rotation will introduce a Doppler effect that will broaden the lines in the spectrum to a considerable extent. One of the limbs of the bright star (in the δ Lib system) is approaching us at the rate of 35 km/sec while the other is receding at the same rate .... These (including orbital velocity changes) are sufficient to account for the general character of the spectrum as we see and photograph it".

Shapley and Nicholson (1919) investigated spectral line profiles in a rotating or pulsating star in connection with Cepheid variables, and showed that an undarkened rotating stellar disk would broaden an infinitely sharp line into a semi-ellipse. Adams and Joy (1919), investigating the short-period variable W UMa, suggested that the unusually broad spectral lines in that system are due ". . . mainly to the rotational effect in each star, which may cause a difference of velocity in the line of sight of as much as 240 km/sec between the two limbs of the star". Estimates of rotational velocities of μ^1 Sco and V Pup from line widths were made by Maury (1920) and (for V Pup) found to agree satisfactorily with computed values by Hellerich (1922).

In an important paper, Shajn and Struve (1929) showed that fast rotational velocities predominate in short-period spectroscopic binaries and developed a graphical method of computing rotationally-broadened line profiles. The resulting "dish-shaped" line contours were observed by Elvey (1929) in a number of broad-lined single stars, with such a ". . . marked similarity . . . with the theoretical contours of rapidly rotating stars obtained by Shajn and Struve . . . that we feel safe in stating that the stars . . .are rotating rapidly". Elvey (1930) followed up this work with a study of rotational broadening of the Mg II 4481 line in 59 O, B, A, and F stars, using the Shajn-Struve graphical method. Instead of using line profiles in the spectrum of the Moon as non-rotating lines, as had been done by Shajn and Struve, Elvey chose profiles from sharp-lined stars of early type. "The stellar disk is divided into sections parallel with the axis of rotation, each section receiving a weight equal to its area expressed as a fraction of that of the total disk. The original contour (i.e., from a sharp-lined star) multiplied by its weight is assigned to each section and displaced by the amount corresponding to the velocity of rotation in the line of sight for the section, and the sum of the contours is taken. The result is the contour of the line for the rotating star. Comparison with observed line profiles then gives v sin i, the component of the rotational velocity in the line of sight". This technique was later used by many investigators.

Struve (1930) summarized the evidence for "Broad and shallow absorption lines in stellar spectra (being) due to axial rotation" and was the first to show that ". . . rotational speed is a function of spectral type, the fastest rotations occurring in the earliest types".

This conclusion was strengthened by a number of statistical studies of line widths in O, B, A, and F stars by Westgate (1933a, 1933b, 1934).

Some 15 years passed before the next flurry of interest in stellar rotation. Using the Shajn-Struve graphical method but including the effects of limb darkening, Slettebak (1949, 1954, 1955, 1956) and Slettebak and Howard (1955) investigated stellar rotation in some 700 stars across the HR diagram using mostly moderate dispersions. Huang (1953) measured line widths in the spectra of 1550 O-G stars, while Herbig and Spalding (1955) made visual estimates of line widths in 656 FO-K5 stars and compared them with line widths in standard stars to obtain v sin i's. A number of high-dispersion studies concentrated on evolved stars. Thus, Oke and Greenstein (1954) used the Shajn-Struve graphical method to study rotation in A, F, and G giant stars; Abt (1957, 1958) compared observed and computed line profiles in high-luminosity A-F stars; Rosendhal (1970) studied line profiles in B and A supergiants; and Danziger and Faber (1972) analyzed stellar rotation among A-F evolved stars. The latter study is interesting in that entire spectral regions, rather than individual lines, were mathematically broadened and compared with observed spectra to obtain rotational velocities. The aforementioned investigations of evolved stars appear to show that solid-body rotation applies to stars which have not expanded too greatly whereas some form of differential rotation applies for the larger, more luminous stars. Other studies of stellar rotation during the 1960's include those of Walker and Hodge (1966), Palmer et al. (1968), and Buscombe (1969). The above plus other references are listed in a review article by Slettebak (1970b).

Lists of v sin i's determined from line profile measurements or visual estimates of line broadening of early-type stars were published by a number of investigators during the past decade or so. Most of the following are high-resolution studies:

Abt and Moyd (1973): late A-type dwarfs
Balona (1975): southern O and B stars
Buscombe and Stoeckley (1975): O, B, and A main-sequence stars
Conti and Ebbets (1977): O-type stars
Day and Warner (1975): sharp-lined B stars
Dworetsky (1974): AO stars
Wolff and Preston (1978): late B-type stars
Wolff et al. (1982): early B-type stars.

A system of 217 bright northern and southern standard stars of types O9-F9 for rotational velocity determinations was established by Slettebak et al. (1975), based on comparisons of theoretical rotationally-broadened profiles with observed profiles from photoelectric scans and coudé spectrograms.

Struve (1930) and Westgate (1934) had shown that ". . .appreciable rotation disappears in the middle F's". High-resolution spectra are therefore required to show measurable line broadening in the later-type stars. Kraft (1967a) was able to study rotation in solar-type stars by employing coudé spectrograms of 4.5-5 Å/mm, giving him an estimated limiting resolution in v sin i of about 6 km/sec. More recently, Soderblom (1982) compared calculated line profiles with observed, high-resolution, echelle spectrograms for solar-type stars. He found that v sin i's as low as 1.5 km/sec and differences in v sin i of < 0.3 km/sec can be discerned for stars rotating as slowly as the Sun. Additional studies of late-type stars using the same techniques were made by Vogt et al. (1983) of BY Dra stars and by Soderblom et al. (1983) of Pleiades K dwarfs.

The determination of rotational velocities of very rapidly rotating stars, as for example the Be stars, involves a number of additional factors. In extreme cases, the stars can no longer be regarded as spherical; gravity darkening is likely to play an important role; and the assumption (inherent in the Shajn-Struve graphical method) that the flux profile of a sharp-lined star can be used to approximate the non-rotating intensity profile at various places on the disk of a rotating star is no longer valid. A crude attempt to incorporate these effects into a line-profile analysis of rapidly-rotating B and Be stars was made by Slettebak (1949). Later papers, using more sophisticated methods, include those by Collins and Harrington (1966), Hardorp and Strittmatter (1968), Stoeckley (1968), Vilhu and Tuominen (1971), Hardorp and Scholz (1971), Hardorp and Strittmatter (1972), Norris and Scholz (1972), and Collins (1974). The latter investigation, in which rotationally-broadened line profiles for O9-F8 main-sequence stars were calculated using the ATLAS model-atmosphere program and taking shape distortion and gravity darkening into account, served as the basis for the aforementioned system of standard stars for rotational velocity determinations (Slettebak et al. 1975).

2.3.2. Fourier Analysis of Line Profiles. Carroll (1933) was the first to suggest the application of Fourier analysis to spectral line profiles for stellar rotational velocity determinations. Since the rotationally-broadened profile is obtained by a convolution, it is advantageous to take the Fourier transform of the observed profile, which is the product of the transforms of the non-rotating profile and of the rotational-broadening function. Comparison of the zeroes of the latter transform with the zeroes of the observed profile allows the determination of v sin i. Carroll and Ingram (1933) applied this method to line profiles published by Elvey (1929, 1930) in several O and B stars and found good agreement with his estimated v sin i's. Later, Colacevich (1937) and Wilson (1969) also applied Carroll's method, the latter to obtain an upper limit of 3.5 km/sec for the rotation velocity of Arcturus.

The introduction of photoelectric scanners to obtain accurate line profiles has made it possible to extend Carroll's method from a location of zeroes to a fitting of the entire transform, thereby adding weight to the measurement. This was first done by Gray (1973) and is the basis of a number of papers by Gray and by M. Smith, primarily on the rotation of G and K stars, plus individual studies of Vega, Arcturus, and Procyon. The method is described and discussed in review articles by Gray (1976), Smith and Gray (1976), Gray (1978), Smith (1979), and Gray (1980a). Other recent investigations of stellar rotation using Fourier transform techniques include those by de Jager and Neven (1982) on Procyon; Ebbets (1979) on O-type stars; and Vogel and Kuhi (1981) on pre-main-sequence stars. In addition to obtaining rotational velocities, many of the aforementioned authors have also measured turbulent velocities as a part of their Fourier analyses, as will be discussed in Section 2.3.4.

Variations of Fourier transform methods have been proposed by several authors. Thus, Deeming (1977) uses a Bessel transform technique in which the Fourier transform is multiplied by a Bessel weighting function and integrated over Fourier frequency, while Milliard et al. (1977) employ the "L_2 norms" of the rotation profile to derive v sin i's for Sirius and Vega.

2.3.3. Other Methods of Line Profile Analysis. Using a PEPSIOS interferometer, Kurucz et al. (1977) observed the profile of an intrinsically narrow Ba II line at 6496.9 Å in the spectrum of Sirius interferometrically and obtained a projected rotational velocity v sin i of 16 km/sec.

Following a method due to Griffin (1967) for measuring radial velocities, Benz and Mayor (1981) use the cross-correlation between the spectrum of a cool star and an appropriate mask located in the focal plane of the spectrograph to obtain stellar rotational velocities. Whereas the position of the correlation dip depends on the radial velocity of the star, the width of the dip depends on the width of the absorption lines chosen for the correlation, and can be used for v sin i measurements. The authors find good agreement between their rotational velocities obtained with the CORAVEL spectrometer and values obtained using Fourier transform techniques.

2.3.4. Rotation Versus Other Line-Broadening Agents. All spectrum lines suffer thermal Doppler and collisional broadening to various degrees, as well as microturbulent broadening and Zeeman broadening in certain types of stars. Fortunately most of these are either small in normal stars or can be avoided (e.g., Stark-broadened Balmer lines are not suitable for rotational velocity determinations).

One broadening agent which competes significantly with rotation in broadening spectrum lines, particularly in early-type stars of high luminosity, however, is macroturbulence (defined as turbulence with elements as large as the thickness of the effective photospheric layers, thereby causing no change in line strengths). Huang and Struve (1960) summarized the earlier work on the recognition and separation of macroturbulence from rotation. Statistical studies (Huang and Struve 1954; Slettebak 1956) had suggested the existence of macroturbulence in early-type stars but it proved to be impossible to distinguish unambiguously from line profile analysis of a single star between rotation and various types of macroturbulence (Huang and Struve 1953; Slettebak 1956; Abt 1958; Rosendhal 1970).

Interest in this problem was revived in the mid-1970's by the application of Fourier analysis to line profiles by Gray, Smith and others. These investigators found (cf. the review paper by Smith and Gray [1976]) that high-resolution, low-noise data make it possible to distinguish, at high frequencies, between the Fourier transform profiles arising from rotation versus those of macroturbulence. They also find evidence for a model of macroturbulence which involves only radial and tangential streams, in contrast to the earlier isotropic Gaussian models. A recent paper by Gray (1984a) points out that Zeeman broadening may also be a significant component of the line broadening in late-type dwarf stars, and comments on the separation of rotation, macroturbulence, and Zeeman effect from line profiles. Other recent attempts to separate macroturbulence from rotation using Fourier analysis include those by de Jager and Neven (1982), who studied Procyon; Ebbets' (1979) study of O-type stars, and Soderblom's (1982) work on solar-type stars.

2.3.5. The Separation of v from i. The determination of stellar rotational velocities from line profile analysis generally yields only the projected (along the line of sight) velocity, v sin i. Information about the true equatorial rotational velocity can be deduced for some special cases, however. Thus, if a large sample of stars of a given spectral type is studied, for example (cf. Slettebak 1966), those stars with the largest observed rotational velocities are presumably being viewed essentially equatorially (sin i = 1) and the observed rotational velocity v sin i must be very close to the equatorial velocity v. The Be stars represent another interesting example. Struve's (1931) rotational model for Be stars suggests that all Be stars of a given type rotate at a very rapid (near critical) rate and that the observed line broadening for a given star depends only upon its inclination angle i. There is statistical evidence for this view (cf. Struve 1951; Slettebak 1976, 1982) -- if the model is adopted, the equatorial velocity for the sample plus inclination angles for individual stars can, in principle, be obtained.

Many investigators have given evidence for a random orientation in space of the axes of rotation in rotating stars. Under these circumstances it is possible, using statistical methods, to obtain a relationship between the mean observed v sin i and the mean true v for a sample of stars (cf. Chandrasekhar and Münch 1950).

The problem of separating v from i for an individual star remains, however. As long as the star is spherically symmetrical, only v sin i can be determined. Very rapid rotation may result in deviations from spherical symmetry, however, as we have seen, and also in gravity darkening and variations in the line profile across the disk of the star. The integrated line profile will then depend upon the inclination and, in principle, v and i can be determined separately. This was first attempted by Stoeckley (1968), who computed rotationally-broadened profiles of several lines and compared them with observed profiles in five rapidly- rotating B and A stars. Later, Hutchings (1976), Hutchings and Stoeckley (1977), and Hutchings et al. (1979) made use of the observed difference in ultraviolet versus visual line widths for rapidly-rotating stars to attempt the separation of i and v for a number of O and B stars. Hutchings and his collaborators assumed spherical stars in their calculations, however, and did not include the variation of the line profile with temperature and gravity. In a more detailed treatment, Sonneborn and Collins (1977) computed rotationally-distorted, gravity-darkened models which include the latitude dependence of T_e and g in their line profiles. Their results were qualitatively similar to those of Hutchings but they predict a smaller ultraviolet-to-visual line width variation. More recently, Ruusalepp (1982) attempted to separate v and i from a study of He I 4471 and Mg II 4481 line widths in a number of B-type stars. Carpenter et al. (1984) have also investigated rotational velocities (for later B-type and A-type stars) as determined from ultraviolet versus visual line profiles, using IUE spectra. They enumerate the various errors and uncertainties which are inherent in such an analysis and suggest that ". . . attempts to separate v from i from line profiles must be carried out with great caution and, indeed, it is not clear to us that such a separation is even feasible."

An interesting special case occurs where v is obtained by means of rotational modulation and v sin i from spectroscopic measurements. This would permit a determination of i and, for a sufficiently large sample, a check on the distribution of i.

3. DIFFERENTIAL ROTATION

No direct information regarding differential rotation (that is, surface rotation as a function of latitude) exists for stars other than the Sun. Slettebak (1949) computed the effects of a solar-type differential rotation on the He I 4026 line profile of a rapidly-rotating model star, using the Shajn-Struve graphical method. The computed profile was deeper and narrower than that for the rigid-body model, but the differences so slight that no meaningful comparison with observed line profiles was possible. Huang (1961) derived a general formula to describe the geometrical broadening of a line profile by differential rotation, but an analytical solution exists only under certain physical conditions. Later, Stoeckley (1968) did attempt to detect differential rotation in five rapidly-rotating B and A main-sequence stars using line profile analysis, and suggested that his objects appeared to be either solid-body rotators or differential rotators in the sense opposite to the solar case. Again, there is a question whether observed line profiles are sufficiently accurate to support such conclusions.

The possibility also exists of detecting differential rotation by means of light variations of rotating stars. Thus, Hall (1972) suggested that a region of tremendous starspot activity darkens one side of the cool component of the RS CVn system and that differential rotation, like that observed in the Sun, then produces the migration of the wave-like distortion in the light curve. Vogt (1975) found period changes in the BY Dra light curves, indicating the presence of differential rotation. Gray (1977, 1982) searched for differential rotation in line profiles of both A-type and F-type stars using Fourier transform techniques, with negative results. Bruning (1981) suggested a numerical model based on Fourier analysis of line profiles to detect differential rotation in late-type stars. He points out that while modulation studies may also be used to determine the amount of stellar differential rotation, the Fourier method retains a certain advantage over K-line index studies since not only the amount but also the sense of differential rotation may be determined. Hallam and Wolff (1981) observed periodic variations in the ultraviolet chromospheric fluxes of H I, Si II, and Mg II in six main-sequence F, G, and K stars, but with period and time dependence of the modulated spectral flux not identical from one ionic species to another in the same star. They attribute this to differential stellar rotation. LaBonte (1982, 1984), however, tried to detect solar differential rotation using data sets analogous to stellar observations (magnetic flux and 2.8 GHz flux) and was not able to do so. The problem of detecting stellar differential rotation is obviously a difficult one.

4. ACCURACY OF ROTATIONAL VELOCITY DETERMINATIONS

4.1. Rotational Modulation

This method of determining stellar rotational velocities has the advantage of being independent of the inclination angle i. It is also very sensitive, allowing rotation rates as slow as 1 km/sec to be measured (Baliunas et al. 1983). On the other hand, the radius of the star must be known in addition to the period of modulation in order to calculate the equatorial rotational velocity. For most stars, the radius must be calculated from the black-body assumption with the effective temperature estimated from the spectral type and the luminosity corrected for interstellar reddening. Including uncertainties in these quantities plus errors in the periods of their light curves, Rydgren and Vrba (1983), for example, estimate errors of ± 16 percent of their derived rotational velocities.

4.2. Eclipsing Binary Radial Velocity Curve Distortions

As stated previously, the determination of equatorial rotational velocities using this method depends upon the "rotation factors" for the time of observation; i.e., how much of the eclipsed star is showing and what is the distribution of light across the disk. These, in turn, will depend upon the elements of the light curve and the assumed limb darkening, among other things. McLaughlin (1933) found v = 200 km/sec for α CrB in this way, but admitted that this value is too large relative to the width of the K-line for that star (Uesugi and Fukuda [1982] list a rotational velocity of 135 km/sec for α CrB, derived from line profile analysis). On the other hand, Kopal (1942), who included limb-darkening in his analysis, claimed a mean error of ± 2 km/sec for his equatorial rotational velocity of Algol of 48 km/sec (Uesugi and Fukuda [1982] give 55 km/sec from line profiles).

It would seem that definitive analyses of rotational distortions in eclipsing binary radial velocity curves to obtain rotational velocities should be carried out, in the manner of Struve and Elvey (1931), using line profiles rather than visual radial velocity measures. The computed line profiles should be based on models which include the effects of limb and gravity darkening, possible shape distortion, and profile changes across the stellar disk. Comparisons with observed line profiles would then yield rotational velocities. Only systems with good photometric solutions should be used and those with known gaseous streams avoided, since the latter may affect the line profiles (Hardie 1950).

4.3. Line Profile Analysis

As was stated very clearly by Abt (1962), the observational precision required and the importance of competing line-broadening agents in addition to stellar rotation varies across the HR diagram. Thus, in A-type main-sequence stars, where the mean v sin i is 125-150 km/sec, the rotational line broadening is likely to dominate other mechanisms such as thermal, microturbulent, or Zeeman broadening. In supergiants, on the other hand, rotational broadening may be comparable to microturbulent and/or macroturbulent broadening.

Careful determinations of v sin i from line widths or line profiles, using moderate-to-high dispersions, seem to agree from one investigator to the next to within about 10 percent. An exception is the determination of the largest rotational velocities (v sin i $>$ 200 km/sec), where the uncertainties may be as large as 15-20 percent of the estimated value (Slettebak et al. 1975). This is due to a number of ambiguities which are introduced when the star rotates close to its critical velocity for which the centrifugal force at the star's equator balances the gravitational force.

A very rough rule for the limit of detection has been stated by a number of investigators (e.g., Treanor 1960; Kraft 1965): the minimum rotational velocity that can be resolved in km/sec is numerically comparable to the dispersion employed in Å/mm.

With regard to visual estimates of line broadening versus measurements from tracings, the opinion stated by Kraft (1967b) seems a valid one: ". . . no real increase in accuracy is obtained from tracings, provided that the visual estimates are based on a sufficiently large number of standards well distributed in spectral type. . . The reason is clear: on a tracing one considers one or two lines only which may be subject to photometric irregularities, whereas visual inspection allows the examination of a number of spectral features at once." This general point-of-view is the basis for the establishment of a system of standard rotational velocity stars by Slettebak et al. (1975).

The internal errors quoted for rotational velocities determined using Fourier transform methods are quite low. Thus, Gray (1980b, 1981a, 1981b) finds mean errors of 0.3-0.4 km/sec for his v sin i's for Vega, Arcturus, and Procyon. Comparison with other determinations show significant differences, however. Gray (1980b), for example, obtains v sin i = 23.4 km/sec for Vega while Milliard et al. (1977) find 18 km/sec. For Procyon, Gray (1981b) lists 2.8 km/sec and De Jager and Neven (1982) 10.0 km/sec. Another example is Sirius: using Fourier transform methods, Smith (1976) finds v sin i = 17 km/sec and Milliard et al. (1977) obtain 11 km/sec, while Kurucz et al. (1977) using an interferometer, find 16 km/sec. The latter write: ". . . we feel that Fourier transform methods should be used with caution unless damping constants, blending, and the continuum level are well determined." In an application of Fourier analysis to A-type stars rotating between 100 and 300 km/sec, Gray (1980c) estimates the internal errors for eleven of his stars to be ". . . no worse than ± 5 km/sec." A comparison with Slettebak et al. (1975) shows that nearly all of his v sin i's fall within ± 10 percent deviation lines.

According to Milliard et al. (1977): ". . . (Fourier transform methods) make use of the whole set of frequency points available in the observed profile, from core to wings; in this sense they are more adequate to obtain v sin i from high resolution and high signal-over-noise data, than methods based on the measure of simply one parameter in the line (usually the half-width)." As Moss and Smith (1981) point out, however, "The main difficulty with this procedure (Fourier analysis) in its original form is that it assumes that there is a unique 'non-rotating profile' that represents the local profile equally at all points on the stellar disk. In practice, the intrinsic profile is likely to vary over the disk, and the de-convolution procedure will yield an unbroadened profile which does not correspond to any real line profile produced by the star. . . . What is required and is now being done is to calculate the transforms by integrations over the disk." Gray (1984b) points out, however, that ". . . in practice, the thermal-microturbulence profile is sufficiently small compared to the rotation-macroturbulence portions that a very approximate calculation is adequate." He suggests furthermore that while disk integrations to combine the effects of rotation and macroturbulence are feasible, the thermal-microturbulence part cannot be done until the small center-to-limb variations seen for the Sun are understood.

5. CATALOGUES AND SELECTED LISTS OF ROTATIONAL VELOCITIES

The first general catalogue of rotational velocities was published by Boyarchuk and Kopylov (1964) and included 2558 stars. A few years later, Uesugi and Fukuda (1970) presented v sin i's for 3951 stars, as did Bernacca and Perinotto (1970, 1971) and Bernacca (1973) for a total of 3074 stars. The most recent list is the revised catalogue of Uesugi and Fukuda (1982) which reviews 11,460 v sin i determinations from 102 sources to give rotational velocities for 6472 stars. All of the aforementioned catalogues have extensive lists of references to the individual papers.

In closing, it may be useful to reference a few lists of rotational velocities of objects which have not been explicitly mentioned earlier in this review. In a number of cases, no up-to-date review papers exist and only the most recent review is cited.

Open clusters: Abt (1970). Individual papers by Abt, Levato, and others since 1970 may be found in the literature.
Binary stars: Slettebak (1963); Van den Heuvel (1970); Weis (1974); Levato (1975).
Ap stars: Preston (1970); Abt et al. (1972).
Be stars: Slettebak (1982).
White dwarfs: Greenstein et al. (1977).
Horizontal-branch stars: Peterson et al. (1983); Peterson (1983).

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DISCUSSION

POLIDAN: I would like to comment on a program we are pursuing with the Voyager UV spectrometers. G. J. Peters, R. Stalio and I are comparing the far-UV (912-1700 Å) flux distributions of a sample of Be stars with sharp-lined stars of similar (ground based) spectral types. Our preliminary conclusions are that there is no significant difference between the FUV flux distributions of the rapidly rotating stars and the sharp-lined stars. This would imply that these Be stars are not rotating at velocities high enough to exhibit gravity darkening effects.

PETERS: Non-radial pulsation may prove to be much more of a problem in the determination of rotational velocities from line profiles than we have recognized thus far. An increasing number of early B stars are being shown to be such non-radial pulsators and the effect on the line profiles is certainly a function of the pulsational phase (i.e., the deduced vsini may be dependent on the time of observation). Furthermore, there is some evidence that an individual star can abruptly change its pulsational modes. As an example of variable absorption lines in a non-radial pulsator, consider recent IUE observations of the active B2 IVe star Mu Cen (Peters 1984 PASP, submitted). The "photospheric" absorption lines were, on the average, considerably broader when H alpha emission was present than during the star's quiescence. Therefore, the deduced vsini from the "photospheric" lines in this "standard" star contained in the reference list of Slettebak et al. (1975) will indeed vary. I suggest that in view of the implied importance of non-radial pulsations that rotational velocity standards be checked for constancy regularly over an extended period of time.

WALKER: I would like to support Dr. Peters' remarks about the effect of non-radial pulsations and the variations in line width. In our study of Spica, published in 1982, we showed that the formal measure of rotational velocity based on line profiles was almost double the old value measured by Struve and others when the star was known to be a Beta Ceph-type variable. Now it has apparently gone into a higher mode and no photometric variability has been detected for over a decade.

Although the interpretation of the "blips" moving through the line profiles is model dependent, there is a consistent acceleration associated with them which must be associated with the rotational velocity and I feel confident that ultimately this will be a useful technique for the determination of rotational velocity.

RAKOS: We have used Fourier methods introduced by Gray on high resolution ultraviolet spectra from IUE. The agreement between our results and the published values was very good.

PARTHASARATHY: How significant is the effect of gravity darkening?

SLETTEBAK: Gravity darkening effects on colors and spectrum lines in rotating stars become important only for values of the fractional angular velocity larger than about 0.9, according to the work of Collins.

LACY: I would like to point out that when the "dip" profile of a radial velocity spectrometer such as CORAVEL is used to estimate the rotational velocity of a double-lined binary, careful attention must be paid to the additional broadening produced by the blending of some of the oppositely displaced features of each component's spectrum. This effect is not present in single star observations but it is significant in most double-lined binaries in all phases and must be taken into account. I believe there has already been at least one analysis of CORAVEL results on YY Gem where this was not done.