Athay, R.G.: 1972, *Astrophys. J. 176*, 659.
Athay, R.G.: 1976, *The Solar Chromosphere and Corona: Quiet Sun*, D. Reidel Publ. Co., Dordrecht.
Auer, L.H.: 1976, *J. Quant. Spectroscopy Radiative Transfer 16*, 931.
Auer, L.H.: 1984, *Methods in Radiative Transfer* (henceforth *MRT*), Cambridge University Press, Cambridge, ed. W. Kalkofen, p. 79.
Canfield, R.C., McClymont, A.N. and Puetter, R.C.: 1984, *MRT*, p. 101.
Cannon, C.J.: 1973, *J. Quant. Spectroscopy Radiative Transfer 13*, 627.
Cannon, C.J.: 1984, *MRT*, p. 157.
Frisch, H.: 1984, *MRT*, p. 79.
Frisch, U. and Frisch, H.: 1975, *Monthly Notices Roy. Astron. Soc. 173*, 167.
Ivanov, V.V.: 1973, *Transfer of Radiation in Spectral Lines*, NBS SP-385 (Washington, D.C.: US Dept. of Commerce).
Kalkofen, W.: 1984, *MRT*, p. 427.
Kalkofen, W.: 1985a, *TRIESTE*.
Kalkofen, W.: 1985b, *TRIESTE*.
Kalkofen, W. and Ulmschneider, P.: 1984, *MRT*, p. 131.
Kwan, J. and Krolik, J.H.: 1981, *Astrophys. J. 250*, 478.
Nordlund, Å.: 1984, *MRT*, p. 211.
Rybicki, G.B.: 1972, in *Line Formation in the Presence of Magnetic Fields*, ed. R.G. Athay, L.L. House and G. Newkirk Jr. (Boulder: High Altitude Observatory), p. 145.
Rybicki, G.B.: 1984, *MRT*, p. 21.
Rybicki, G.B.: 1985, *TRIESTE*.
Scharmer, G.B.: 1981, *Astrophys. J. 249*, 720.
Scharmer, G.B.: 1983, *Astron. Astrophys. 117*, 83.
Scharmer, G.B.: 1984, *MRT*, p. 173.
Scharmer, G.B. and Carlsson, M.: 1984, *J. Comp. Phys.*, in press.
Scharmer, G.B. and Nordlund, Å.: 1982, *Stockholm Obs. Rep. 19*.
Stenholm, L.G.: 1980, *Astron. Astrophys. Suppl. 42*, 23.
Stenholm, L.G. and Stenflo, J.O.: 1977, *Astron. Astrophys. 58*, 273.
Stenholm, L.G. and Stenflo, J.O.: 1978, *Astron. Astrophys. 67*, 33.
Wehrse, R.: 1985, *TRIESTE*.

## 2. Manifestations of the Interaction between Convection and Rotation in Stellar Atmospheres (Lee Hartmann)

Introduction. According to dynamo theories, the interaction between convection and rotation is responsible for the generation of magnetic fields in solar-type stars. Stellar observations can explore the ways the global parameters, like the surface rotation and internal structure, affect the production of magnetic fields. In this very brief review I wish to concentrate on recent progress in understanding the evolution of stellar rotation, and the dependence of stellar cycles and magnetic activity on rotation, internal structure, and age.

Stellar Rotation. Most of the progress that has been made in understanding the origins of magnetic activity derives from an explosion in the amount of stellar rotation data. The measurement of rotational modulation of the Ca II emission in slowly-rotating main sequence stars (Baliunas et al. 1983) has now provided a large sample of stars for which the rotational periods are accurately known. Modulation of broad-band photospheric light by starspots even makes it possible to determine accurate rotational periods for stars in the Hyades (Lockwood et al. 1983).

One of the biggest surprises in this area is the discovery that late-type dwarfs go through a phase of very rapid rotation (van Leeuwen and Alphenaar 1982; Soderblom, Jones and Walker 1983; Stauffer et al. 1984). Low-mass stars apparently spin up (by a factor of 10!) as they contract toward the main sequence (Stauffer et al. 1984). Furthermore, the observation of rapid rotation among G dwarfs in the α Per cluster (Stauffer et al. 1985), compared with the slow rotation of similar stars in the Pleiades cluster (cf. Benz, Mayor and Mermilliod 1984) shows that many solar-type stars go through a phase of rapid spin-down (from ~50 to ~10 km $s^{-1}$ ) between the ages of $5 \times 10^7$ and $7 \times 10^7$ years. While the implications of this behavior are not fully

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clear, we now have a sample of rapidly-rotating, single dwarfs to test dynamo theories in an expanded range of rotation.

Solar-Type Cycles. Solar and stellar cycles (Wilson 1978) provide the fundamental evidence for dynamo generation of stellar magnetic fields. The extension of the Mt. Wilson survey work has made it possible to investigate the dependence of cycle periods on rotation and other parameters in detail. Noyes, Weiss and Vaughan (1984) found a relationship between cycle period and rotational period for a sample of 13 slowly-rotating main-sequence stars of the form $P(\text{cycle}) \approx P(\text{rot})^n$, $n$ = 1.25±0.5. They suggest that the range of values found for the exponent $n$ apparently rules out quenching of the $\alpha$ effect or differential rotation as mechanisms limiting dynamo action, but is consistent with the effects of magnetic buoyancy.

These results must be considered preliminary since ten of the 13 stars have not yet been observed for two cycle periods. In addition, this sample does not include the more active, rapidly rotating stars. In a recent study of the Mt. Wilson data, Baliunas et al. (1985) conclude that the range of periods among the active stars is very large, and no relationship between rotation and cycle length is present in the larger sample. Short cycle periods have also been seen in rapidly-rotating RS CVn systems (Dorren and Guinan 1984; Brusso et al. 1984), although the different internal structure of these evolved stars make comparison difficult.

Dependence of Magnetic Activity on Rotation and Internal Structure. One would like to use direct observations of stellar magnetic fields to determine the dependence of field generation on rotation and internal structure. However, it is clear from recent studies that the detection of magnetic fields is extremely difficult (Marcy 1984; Gray 1984; Borra et al. 1984). Measurements of photometric variability can be used to infer some aspects of starspot activity; the results of Radick et al. (1982) and Lockwood et al. (1983) indicate that spot activity in the Hyades cluster is much weaker in F than in G dwarfs.

One of the most useful tracers of stellar magnetic activity is Ca II H and K emission, because fluxes can be measured accurately, the emission has been observed in a large number of stars, and the time baseline of observations is sufficiently long to reduce the effects of variability. Although a number of investigations clearly demonstrate the correlation between chromospheric emission and rotation (Middelkoop 1982a; Catalano and Marilli 1983; Noyes et al. 1984), they unfortunately all differ on the dependence of emission on rotation and spectral type.

This disagreement is produced by a number of theoretical and observational difficulties. Theories of magnetic field generation and the resulting chromospheric emission are not sufficiently well developed to predict the fundamental parameters controlling chromospheric emission. One has to infer the proper parameters to study from observations. Unfortunately, many stellar parameters are correlated, and although techniques exist to find combinations of parameters that minimize the scatter of data points (cf. Schrijver 1983), these analyses usually assume straight-line relationships that are not clearly justified. Finally, there are arguments about the proper way to disentangle chromospheric and photospheric emission (Blanco et al. 1974; Linsky and Ayres 1978; Catalano and Marilli 1983; Hartmann et al. 1984).

Noyes et al. (1984) showed that the dimensionless ratio of chromospheric to bolometric luminosity is determined by rotation and a function of spectral type. Noyes et al. identified this spectral-type dependent function as the convective turnover timescale $\tau$, so that the dimensionless activity parameter is defined as a function of the ratio of $\tau$ to the rotational period, otherwise known as the Rossby number (see also Mageney and Praderie 1984). This parameterization is also motivated by the idea that the Rossby number is closely related to the dynamo number (Durney and Latour 1978; Parker 1979).

Although the description of Noyes et al. is attractive, it must be emphasized that this formulation is not unique, and that observations at present do not rule out that other parameterizations could be used which would also provide a tight relation between some aspects of rotation and chromospheric emission. Because of the close relation between chromospheric and coronal activity (Ayers, Marstad and Linsky 1981; Oranje, Zwaan and Middelkoop 1982; Schrijver 1983; Vilhu and Rucinski 1983, Vilhu 1984), it appears that any successful parameterization of chromospheric activity

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will apply to other magnetic field-related emission.

Evolution of Magnetic Activity. The apparent bimodal distribution of chromospheric emission in the Vaughan and Preston (1980) survey led to suggestions that rapid rotators have a qualitatively different dynamo activity than slow rotators, and that there is a discontinuous change in activity at a critical rotation rate (Knobloch, Rosner and Weiss 1981; Durney, Mihalas and Robinson 1981). In a statistical analysis of the Vaughan-Preston survey, Hartmann et al. (1984) pointed out that a discontinuous change in emission as a function of age is not required by the observations. They did suggest that the survey, and framgmentary observations of the Pleiades, indicated weaker chromospheric activity among young stars than predicted by the Skumanich (1972) relation. Deviations from the Skumamich relation were also found by Barry, Hege and Cromwell (1984). Furthermore, studies of coronal X-ray activity also indicate a weaker dependence of activity on age and/or rotation for young, rapidly rotating stars than for older, more slowly-rotating objects (Stern et al. 1981; Walter 1982; Schrijver 1983; Vilhu 1984; Caillault and Helfand 1984; Walter et al. 1984).

Some progress has also been achieved in the analysis of magnetic activity for evolved stars. Simon (1983) found that the C IV emission in giants drops off extremely rapidly near spectral type G8. These results are very reminiscent of the rapid decrease in Ca II emission among giants in the mass range ~3-1.7 $M_\odot$ observed by Middelkoop (1982b), providing new insights into the decay of dynamo activity as stars evolve.

## References


Ayres, T.R., Marstad, N.C. and Linsky, J.L.: 1981, *Astrophys. J. 247*, 545.
Baliunas, S.L., Vaughan, A.H., Hartmann, L., Middelkoop, F., Mihalas, D., Noyes, R.W., Preston, G.W., Frazer, J. and Lanning, H.: 1983, *Astrophys. J. 275*, 752.
Baliunas, S.L. et al.: 1985, *Bull. Amer. Astron. Soc.*, in press.
Barry, D.C., Hege, K. and Cromwell, R.H.: 1984, *Astrophys. J. (Letters) 277,* L65.
Benz, W., Mayor, M. and Mermilliod, J.C.: 1984, *Astron. Astrophys. 138,* 93.
Blanco, C., Catalano, S., Marilli, E. and Rodono, M.: 1974, *Astron. Astrophys. 33,* 257.
Borra, E.F., Edwards, G. and Mayor, M.: 1984, *Astrophys. J. 284,* 211.
Brusso, M., Scaltriti, F., Blanco, C., Catalano, S., Marilli, E., Pazzani, V.and Rodono, M.: 1984, *Astron. Astrophys. 135,* 255.
Caillault, J.P. and Helfand, D.: 1985, *Astrophys. J.,* in press.
Catalano, S. and Marilli, E.: 1983, *Astron. Astrophys. 121,* 190.
Dorren, J.D. and Guinan, E.F.: 1984, in *Cool Stars, Stellar Systems, and the Sun,* eds. S.L. Baliunas and L. Hartmann (Springer, Heidelberg), p. 259.
Durney, B.R. and Latour, J.: 1978, *Geophys. Appl. Fluid Dyn. 9,* 241.
Durney, B.R., Mihalas, D. and Robinson, R.: 1981, *Publ. Astron. Soc. Pacific 93,* 537.
Gray, D.F.: 1984, *Astrophys. J. 277,* 640.
Hartmann, L., Soderblom, D.R., Noyes, R.W., Burnham, N. and Vaughan, A.H.: 1984, *Astrophys. J. 276,* 254.
Knobloch, E., Rosner, R. and Weiss, N.O.: 1981, *Monthly Notices Roy. Astron. Soc. 197,* 45P.
Linsky, J.L. and Ayres, T.R.: 1978, *Astrophys. J. 220,* 618.
Lockwood, G.W., Thompson, D.T., Radick, R.R., Osborn, W.H., Baggett, W.E., Duncan, D.K. and Hartmann, L.W.: 1984, *Publ. Astron. Soc. Pacific 96,* 714.
Margeney, A. and Praderie, F.: 1984, *Astron. Astrophys. 130,* 143.
Marcy, G.W.: 1984, *Astrophys. J. 276,* 286.
Middelkoop, F.: 1982a, *Astron. Astrophys. 107,* 31.
Middelkoop, F.: 1982b, *Astron. Astrophys. 113,* 1.
Noyes, R.W., Hartmann, L., Baliunas, S.L., Duncan, D.K. and Vaughan, A.H.: 1984, *Astrophys. J. 279,* 763.
Noyes, R.W., Weiss, N.O. and Vaughan, A.H.: 1984, *Astrophys. J.*, in press.
Oranje, B.J., Zwaan, C. and Middelkoop, F.: 1982, *Astron. Astrophys. 110,* 30.
Parker, E.N.: 1979, *Cosmic Magnetic Fields,* Clarendon Press, Oxford.
Radick, R.R., Lockwood, G.W., Thompson, D.T., Warnock III, A., Hartmann, L.W., Mihalas, D., Worden, S.P., Henry, G.W. and Sherlin, J.M.: 1983, *Publ. Astron. Soc. Pacific 95, 621.*


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Schrijver, C.J.: 1983, *Astron. Astrophys. 127*, 289.
Simon, T.: 1984, *Astrophys. J. 279*, 738.
Skumanich, A.: 1972, *Astrophys. J. 171*, 565.
Soderblom, D.R., Jones, B.F. and Walker, M.F.: 1983, *Astrophys. J. (Letters) 274*, L37.
Stauffer, J.R., Hartmann, L., Soderblom, D.R., Burnham, N.: 1984, *Astrophys. J. 280*, 202.
Stauffer, J.R., Hartmann, L., Burnham, N. and Jones, B.: 1985, *Astrophys. J.*, in press.
Stern, R.A., Zolcinski, M.-C., Antiochos, S.K. and Underwood, J.H.: 1981, *Astrophys. J. 249*, 647.
van Leeuwen, F. and Alphenaar, P.: 1982, *ESO Messenger* No. *28*, 15.
Vaughan, A.H. and Preston, G.W.: 1980, *Publ. Astron. Soc. Pacific 92*, 385.
Vilhu, O.: 1984, *Astron. Astrophys. 133*, 117.
Vilhu, O. and Rucinski, S.M.: 1983, *Astron. Astrophys. 127*, 5.
Walter, F.M.: 1982, *Astrophys. J. 253*, 745.
Walter, F.M., Linsky, J.L., Simon, T., Golub, L. and Vaiana, G.S.: 1984, *Astrophys. J. 281*, 815.
Wilson, O.C.: 1978, *Astrophys. J. 226*, 379.

3. Wolf-Rayet star atmospheres (David C. Abbott)

Introduction. Wolf-Rayet (WR) stars are the helium-burning remnants of massive stars (initial mass $\gtrsim 30\ M_\odot$), which have lost their outer hydrogen-rich layers through the processes of Roche lobe overflow to a companion or mass loss by a strong stellar wind. The characteristic emission-line spectrum which defines the WR spectral type is produced by a stellar wind that is so dense and opaque, that the radiation of all lines and continua arise from material in the wind. Because the wind completely screens any radiation emitted by the hydrostatic core of the star, the spectra of WR stars are nearly impossible to interpret quantitatively, and the basic parameters -- such as mass, luminosity, temperature, and chemical composition -- are poorly determined.

Model Atmospheres for Wolf-Rayet Stars. Classic model atmospheres are clearly inappropriate for WR stars because of the flagrant violation of hydrostatic equilibrium and planeparallel geometry. There is no analog to the "photospheric analysis" of OB stars, which yields $T_{eff}$, log g, chemical composition, and the continuum radiation field. Spectral lines formed in the winds of WR stars cannot be analyzed empirically like their OB star counterparts (e.g. Castor and Lamers 1979) because: (i) Collisional processes cannot be ignored in the statistical equilibrium, as evidenced by the large observed ratio of emission to absorption in the P Cygni profiles. (ii) Radiative rates are not known a priori because the continuum radiation field depends on the run of both density and temperature in the wind. (iii) Almost all wind profiles overlap in frequency with other wind lines because of the Doppler-shift imposed by the expansion velocities. Photons of a given frequency will scatter multiply with several distinct lines in the wind, so the statistical equilibrium of different elements is interlocked by the radiation field.

Given these formidable difficulties it is no wonder that, to my knowledge, no line profile of a WR star has ever been fitted by a theoretical model to derive quantitative knowledge about the atmospheric structure. The basic means of interpreting WR winds remains the escape probability formalism of Castor and Van Blerkom (1970), in which the statistical equilibrium is solved at a "representative point" in the wind. This method essentially fits the total intensity of the observed lines, but does not utilize any information available in the line shape.

Fortunately, progress in the analysis of WR spectra appears imminent. At least three researchers are developing diagnostic models which are intermediate between present crude models and the prohibitive solution of the general problem. All use a semiempirical approach, in which $T(r)$ and $\rho(r)$ are assumed, and the radiation

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