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MEASUREMENTS OF MAGNETIC FIELDS IN YOUNG MAIN-SEQUENCE STARS

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ABSTRACT

The Zeeman analyzer at the coudé spectrograph of the 224-cm (2.2-m) telescope on Mauna Kea has been used to search for magnetic fields in young main-sequence stars at a dispersion of 3.3 Å mm^{-1}. Eight stars of spectral types F0 V–K0 V were selected as young stars by one or more criteria: intense Ca II emission cores, high Li content, high axial rotation. Four of the stars clearly show no detectable magnetic fields and a fifth one probably has no field. Ten spectrograms of γ Vir N indicate that it does have a small, possibly variable magnetic field. There is marginal evidence in favor of weak magnetic fields in the two coolest stars, ξ Boo A and 70 Oph, both of which show intense Ca II emission.

Subject headings: Ca II emission — late-type stars — magnetic fields

I. INTRODUCTION

The work of Babcock and Babcock (1955) showed a spatial correlation on the solar surface between the intensity of the Ca^+ plage areas and the bipolar magnetic regions. More detailed work (e.g., Howard 1959; Leighton 1959; Simon and Leighton 1964) at lower field strengths has further revealed the almost one-to-one spatial correspondence between Ca^+ emission (K2) intensity and magnetic field strength. In regions on the Sun where the chromospheric activity is high, the magnetic field is high. This suggests that stars with active chromospheres might also show detectable magnetic fields. A large-scale field or small-scale but intense fields can be measured by conventional Zeeman spectroscopy.

The intensity of stellar Ca^+ emission has been shown to be correlated with age for main-sequence stars by Wilson (1963) and Wilson and Skumanich (1964). This has been attributed to the decay of magnetic fields and chromospheric activity with time. Thus the stars most likely to reveal magnetic fields are young main-sequence stars.

Three spectroscopic criteria for youth in main-sequence field stars have been established: intense Ca^+ emission (Wilson 1963), high Li abundance (Herbig 1965), and high axial rotation (Kraft 1967). Wilson's original work is based on a study of the Ca^+ emission in main-sequence stars in the general field, in visual binaries, and in galactic clusters. The correlation has been further confirmed by identifying the young main-sequence stars by Strömgren photometry (Wilson and Skumanich 1964) and by kinematical motions (Wilson and Woolley 1970).

Herbig (1965) has found that main-sequence Li abundances are correlated with age-dependent parameters such as Ca II emission intensity, space velocity, and metal abundance in the sense that the younger stars have more Li. He further showed that while the main-sequence lifetime increases toward cooler spectral types, the observed range of Li abundance decreases from F- to G- to K-type stars. In addition, Herbig (1965), Danziger (1967), and Zappala (1972) have all studied the Li content of main-sequence stars in galactic clusters of known ages and have confirmed the age correlation.

Kraft (1967) discovered that main-sequence field stars with Ca^+ emission detectable at 10 Å mm^{-1} have higher than average axial rotational velocity for their spectral type. His study of the rotational velocities of solar-type stars in the Pleiades and Hyades clusters revealed the highest velocities for a given mass in the Pleiades (age $\sim 3 \times 10^7$ years), intermediate velocities for the Hyades (age $\sim 4 \times 10^8$ years) and the "field emission" stars, and lowest velocities for field stars with no Ca^+ emission. It is thought (Kraft 1967; Wilson 1966) that magnetic braking is responsible for slowing the rotation as the star ages. Angular momentum is lost through a magnetically coupled stellar wind.

From the above work it is concluded that as a star ages, its magnetic field declines, the intensity of Ca^+ emission (and other signs of chromospheric activity) decreases, the Li atoms are slowly depleted, and the axial rotation rate declines. The stars observed for this work are all young by one or more of these criteria: intense Ca^+ emission, high Li content, rapid rotation.

II. OBSERVATIONS

All observations were made with the Zeeman analyzer at the coudé spectrograph of the 224-cm reflector at the Mauna Kea Observatory. The apparatus is described by Wolff and Bonsack (1972). The spectrograms, all on baked IIa-O emulsion, have a dispersion of 3.4 Å mm^{-1} and cover the wavelength range 3600–4800 Å. The spectra were widened to between 0.4 and 0.6 mm on the plate for each sense of polarization.

Table 1 lists the eight stars that were observed and their spectral class. The [Li/Ca] values, Ca^+ emission

TABLE 1

STARS OBSERVED AND RESULTS

Star	Spectral Type	[Li/Ca]	Ca^+	$v \sin i$ (km/s^{-1})	H_e (gauss)	p.e. (n) (gauss)	p.e. (N) (gauss)
γ Vir N..........	F0 V	2.1*	wk‡	16‡	−330–+436	+83 (54)	
γ Vir S..........	F0 V	1.7*	...	22‡	+207	±60(122)	± 91(6)
ι Peg..........	F5 V	1.3†	...	7#	− 13	±16(179)	± 31(4)
γ Ser..........	F6 V	1.0*	(1502)§	7#	−142	±47 (95)	±161(3)
θ Boo..........	F7 V	...	1‖	32#	+208	±83 (65)	±152(3)
χ Her..........	F9 V	1.5†	(1377)§	≤ 6#	− 27	±16(168)	± 16(4)
ξ Boo A..........	G8 V	1.4†	5‖	...	+142	±19(172)	± 34(4)
70 Oph..........	K0 V		3‖	...	−115	±22(166)	± 13(4)

* Danziger and Conti 1966. † Herbig 1965. ‡ Warner 1968.
§ Wilson 1968. ‖ Wilson and Bappu 1957. # Kraft 1967.

intensities, and rotational velocities are given where known. Both γ Vir N and ξ Boo A fulfill two criteria of youth: Ca^+ emission and high Li abundance.[1] γ Vir S, ι Peg, γ Ser, and χ Her were selected for their high Li content, 70 Oph for its strong Ca^+ emission, and θ Boo since its rotation is higher than typical F7 dwarfs. In addition, θ Boo shows Ca^+ emission which is rare at F7. Although χ Her has a high Li/Ca abundance ratio, its high space velocity and low metal content indicate that it may be an old main-sequence star. The last three columns of table 1 will be discussed in the next section.

Wavelength measurements were made on a Grant comparator which allows accurate, separate measurements of the two spectra of opposite polarization. The same master line list of 54 lines was used for all stars from which 20–50 lines were measured on each plate. The exact number measured depended on the line breadths, line blending, and spectral type of each star. The effective longitudinal magnetic field, H_e, is found from the slope of the least-squares line from the linear relationship between the z-value of the Zeeman pattern and the measured shift for each line.

III. RESULTS

The last three columns of table 1 give the results of the measurements of the longitudinal magnetic field, H_e, and two estimates of the probable error of the field. The first probable error gives the probable error from the internal consistency of the field measured by each line. The number of lines, n, measured on all plates is given in parentheses. The second probable error shows the dispersion in the mean magnetic field from plate to plate with N, the number of plates which were measured, given in parentheses. The second measure of the probable error is the more significant and should be applied for stars with nonvariable magnetic fields. Preston (1969) points out that even though the plate is aligned carefully, a typical residual alignment error of 100 gauss is possible. For most of the stars measured in this work, there were four independent plates and four independent alignments and the residual alignment error is included in the probable errors in table 1.

For the stars ι Peg, γ Ser, θ Boo, and χ Her there is clearly no detectable magnetic field beyond the probable errors. Both χ Her and ι Peg have near zero values with very small probable errors. Both stars have very sharp lines and those results imply that there is no zero-point error in H_e and little systematic bias in the analyzer or in the measurement technique. [Recent measurements by Bonsack (private communication) on a standard sharp-lined F4 V star, θ Cyg, confirm this. His mean H_e from four 3.4 Å mm^{-1} spectrograms is 51 ± 26 gauss.] The three plates measured for γ Ser and θ Boo show such wide differences, as indicated by the second probable error, that the resulting means for H_e are not significant. Since the lines in θ Boo are quite broad ($v \sin i$ = 32 km s^{-1}), they are difficult to measure.

The star γ Vir S also has broad lines and fewer measurable lines due to blending. The six individual plates all give positive fields ranging from 84 to 438 gauss. Although the internal probable error is respectably small, the mean H_e of 208 gauss is hardly more than twice the probable error calculated from the agreement among the six plates. The conclusions for γ Vir S are uncertain; it seems unlikely that it has a magnetic field measurable by this technique.

Both ξ Boo A and 70 Oph show small, but internally consistent, measured fields. The internal probable errors are very small, $\sim \pm 20$ gauss, and the agreement from plate to plate is excellent. These two stars are the coolest stars in the group; both have extremely sharp lines and were easy to measure. The mean fields are about 4–9 times the probable errors. Since the fields are small, however, more spectrograms should be obtained to confirm or reject these results.

The individual results for γ Vir N are collected in table 2. Babcock's (1958) data (which give H_e = −390 gauss) and the material collected in 1971 and 1972 indicated that γ Vir N has a small magnetic field that is apparently variable. The maximum rotation period for this F0 V star with measured $v \sin i$ = 16 km s^{-1} is P = 4.27 days. In order to determine if the field variation has such a short period, five

[1] γ Vir N has very weak Ca^+ emission, but it is the hottest star known to have such emission (Warner 1968). Although it lies outside the range on the main sequence where the age-Ca^+ emission correlation has been established, its very high Li content indicates that it is young.

TABLE 2

RESULTS FOR γ VIRGINIS N

Plate No.	Julian Date 2,440,000+	H_e (gauss)	p.e. (n) (gauss)
170	1079.78	−330	±126(31)
177	1081.76	− 58	± 76(55)
514	1462.76	+436	± 65(51)
542	1484.76	+ 70	±110(35)
546	1486.77	+217	± 96(38)
777	1719.91	+306	± 78(67)
782	1720.93	+340	± 75(62)
785	1721.90	+251	± 67(65)
788	1722.91	+268	± 78(67)
791	1723.91	+201	± 59(69)

Zeeman spectrograms were obtained on five successive nights. The last five entries in table 2 give those results. No meaningful short-term variation was found. The mean field measured on those five nights is +273 gauss with a plate-to-plate probable error of ±36. Unfortunately, the effective wavelength resolution on those five plates is appreciably less than on the other plates, so it is possible that small variations (250 gauss) could have gone undetected. However, the measured variability of the field from ∼ −400 gauss (Babcock 1958) to ∼ +400 gauss does appear to be unrelated to rotation.

IV. CONCLUSIONS

There is little doubt as to the reality of the small field in γ Vir N. As Warner (1968) reports, this star is the hottest star which shows Ca^+ emission, which implies that it has a highly active chromosphere. The presence of the magnetic field can be understood in this context. The apparent variability of the field could be due to a real time variation in the chromospheric activity.

It is noteworthy that the only other two stars in this group of eight which potentially indicate the presence of a magnetic field, ξ Boo A and 70 Oph, also have very strong Ca^+ emission for their spectral type.

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